Injection and Staging for Laser Plasma Accelerators

Anthony Gonsalves
LOASIS Program
Lawrence Berkeley National Laboratory

AAC 2012

http://loasis.lbl.gov/

U.S. DEPARTMENT OF ENERGY | Office of Science

Thank you for your input

Imperial College London

BERKELEY LAB

Texas Center for High Intensity Laser Science
Petawatt

WE'RE TEXAS

UCSD

UR LLE

UCLA

UR LLE

ÉCOLE POLYTECHNIQUE ParisTech

cnrs

ENSTA ParisTech

loa

LULI

JAEA

NRL Plasma Physics Division

UNIVERSITY OF OXFORD

TECH-X

MPQ

UNIVERSITY OF MARYLAND

SIOM
中国科学院上海光学精密机械研究所

Outline

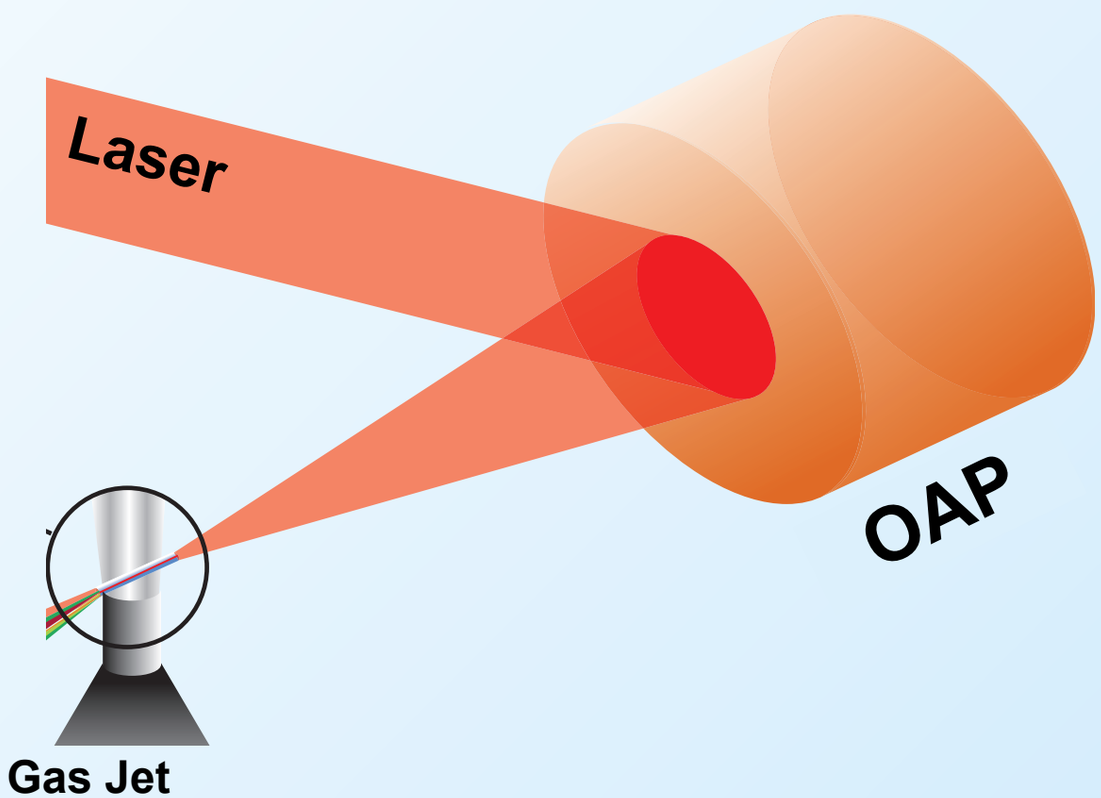
- Intro to LPAs and self injection
- Additional injection techniques
  - Colliding pulse
  - Ionization
  - Density tailoring
- Staging

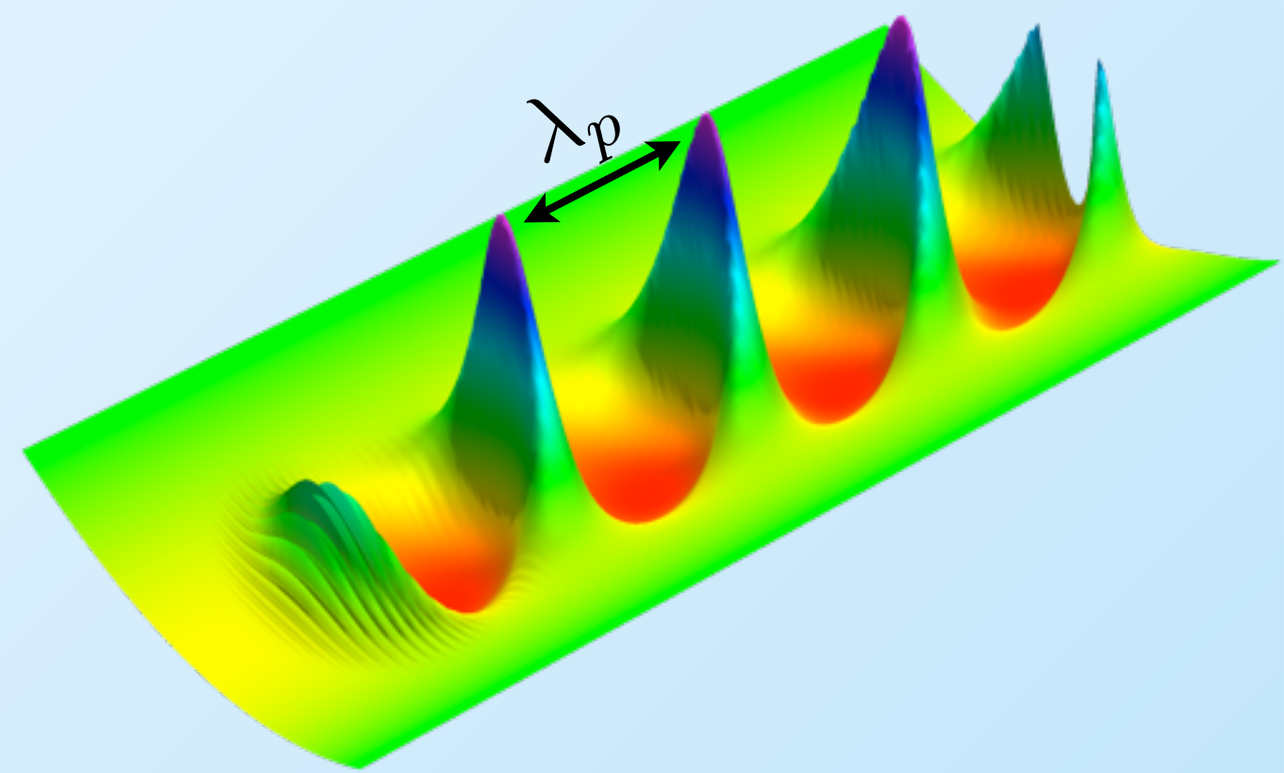
LPAs are Compact Femtosecond Accelerators

- Plasma accelerators - Ultra-high axial electric fields

$$E_0 = \frac{m_e \omega_p c}{e} \approx 100\,\mathrm{GV/m} \quad \text{for} \quad n \approx 10^{18}\,\mathrm{cm}^{-3}$$

  - COMPACT ACCELERATORS
- Can excite large plasma waves with ponderomotive force of intense laser pulse
- Plasma wavelength ~10s micron → femtosecond beams

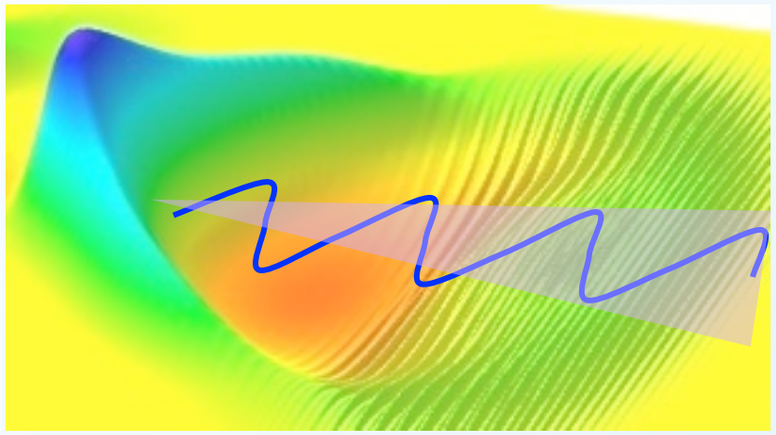




T. Tajima and J.Dawson, *PRL*, 43, (1979) 267; Esarey et al., Rev. Mod. Phys. 81, 1229–1285 (2009)

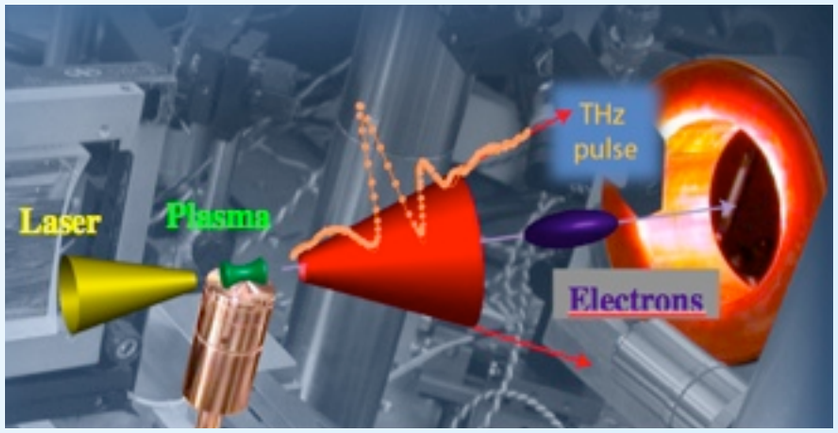
Laser Plasma Accelerator Explored For Light Sources

Betatron radiation during acceleration – Multi keV



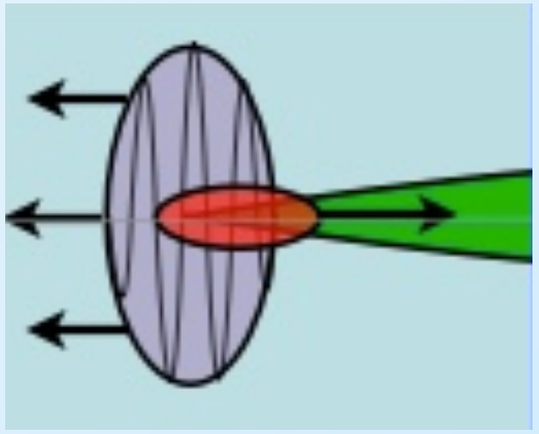
Rousse et al., Phys. Rev. Lett. 93, (2004)
Esarey et al., Phys. Rev. E 65, (2002)

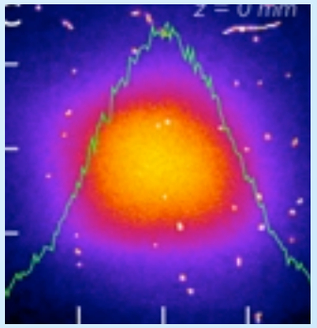
Transition radiation from beam exiting plasma – MV/cm THz



Leemans et al., Phys. Rev. Lett. 91, (2003)

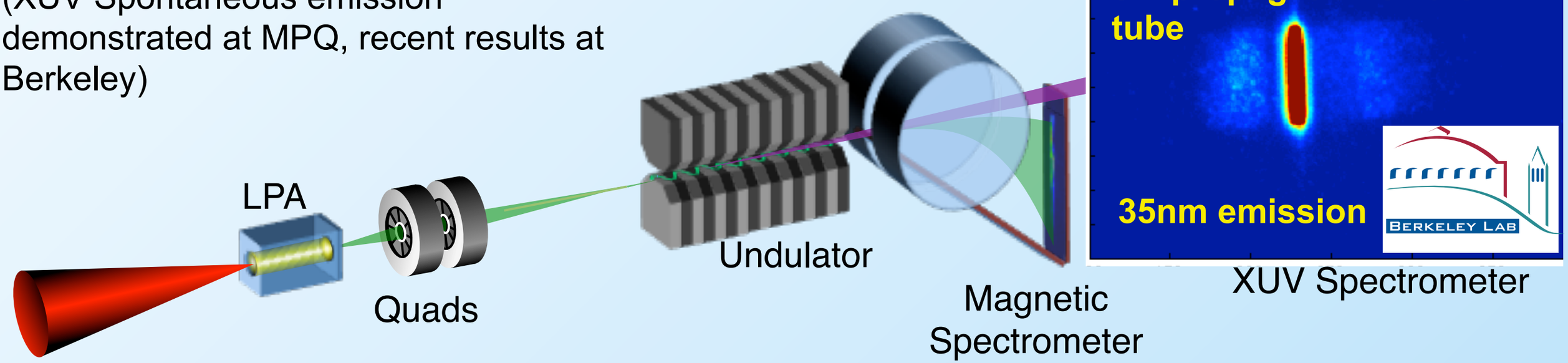
Thomson Scattering – Multi keV/ MeV x-ray/gamma ray





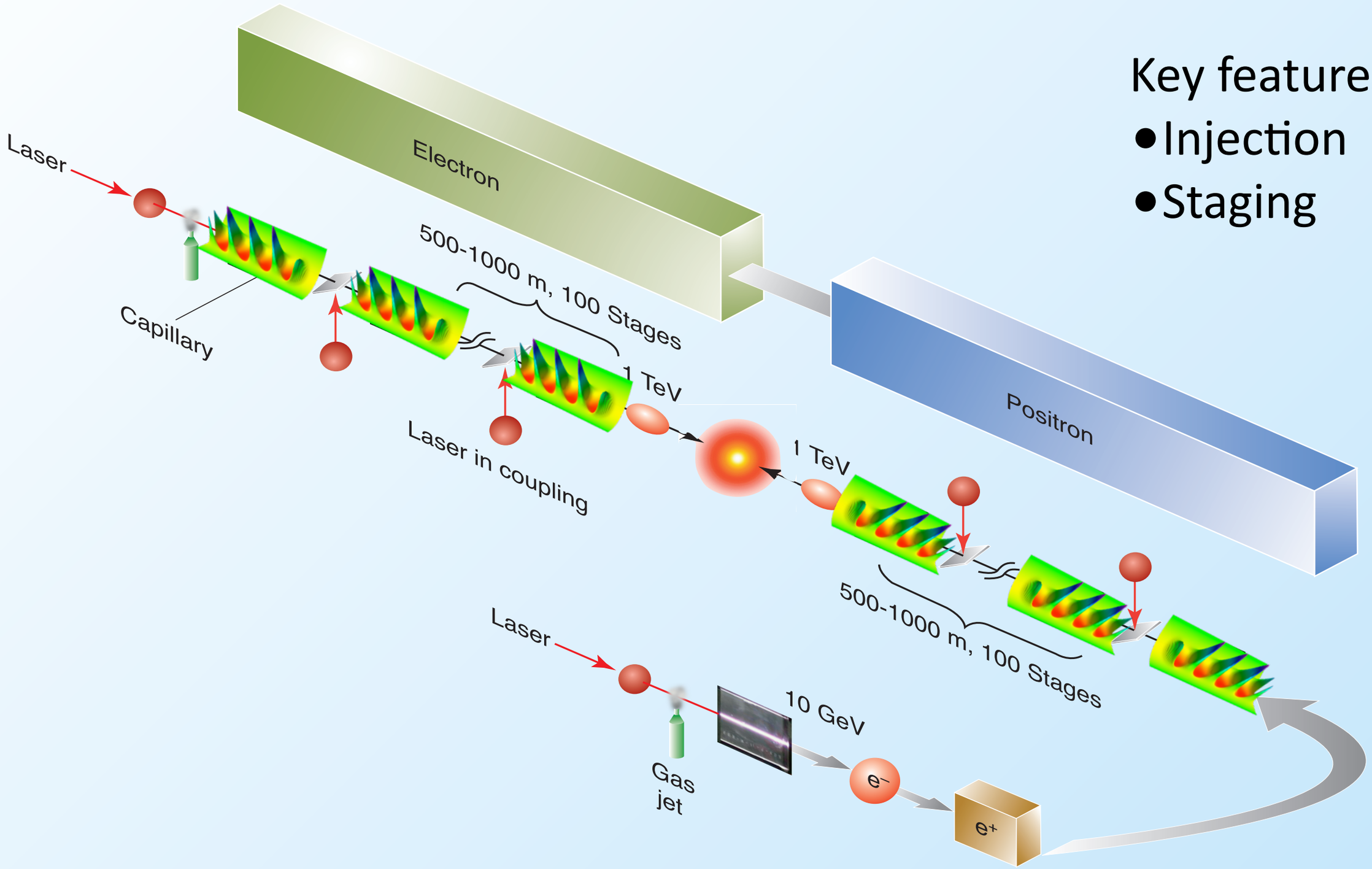
K. Ta Phuoc *et al.*, Nature Photonics (2012)

Free Electron Laser
(XUV Spontaneous emission demonstrated at MPQ, recent results at Berkeley)



Fuchs et al.,Nature Physics (2009)

Laser Plasma Accelerator Explored For Linear Colliders: Follow Paradigm Of Conventional Accelerators To Increase Beam Energy And Quality

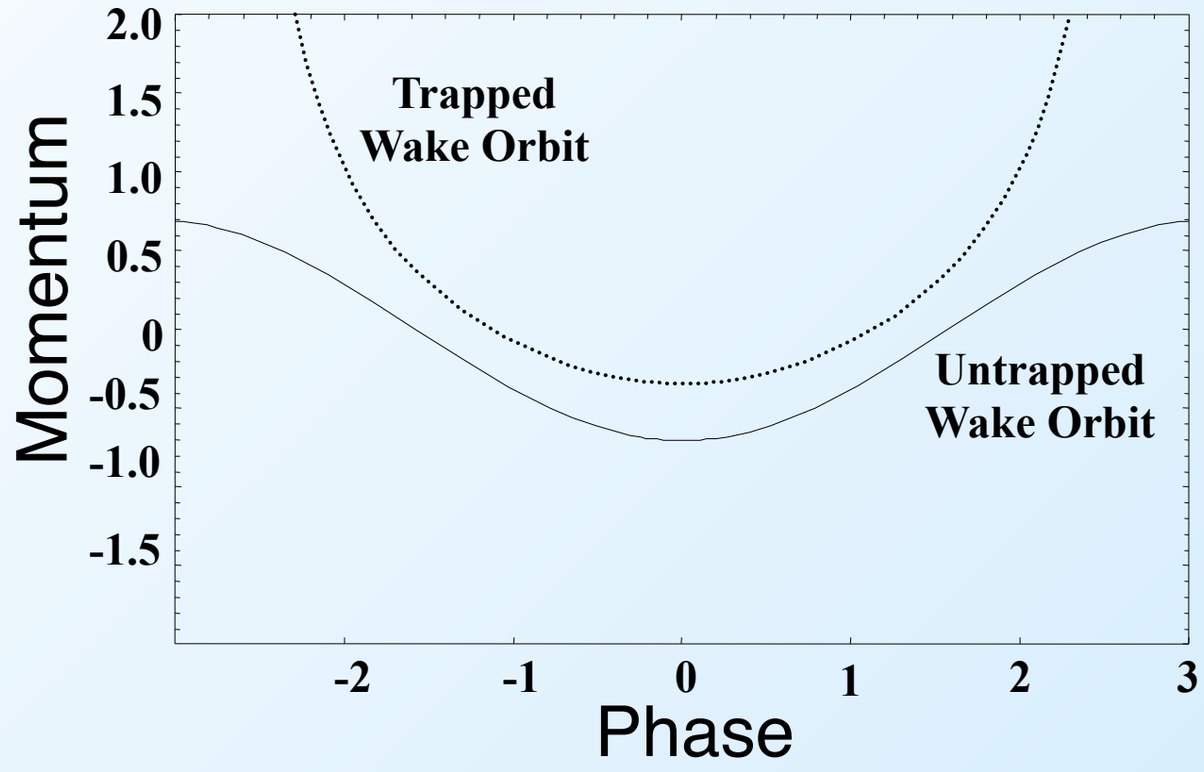


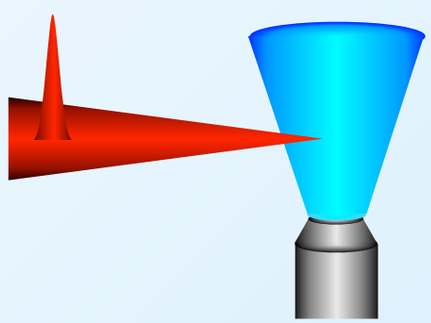
Key features:

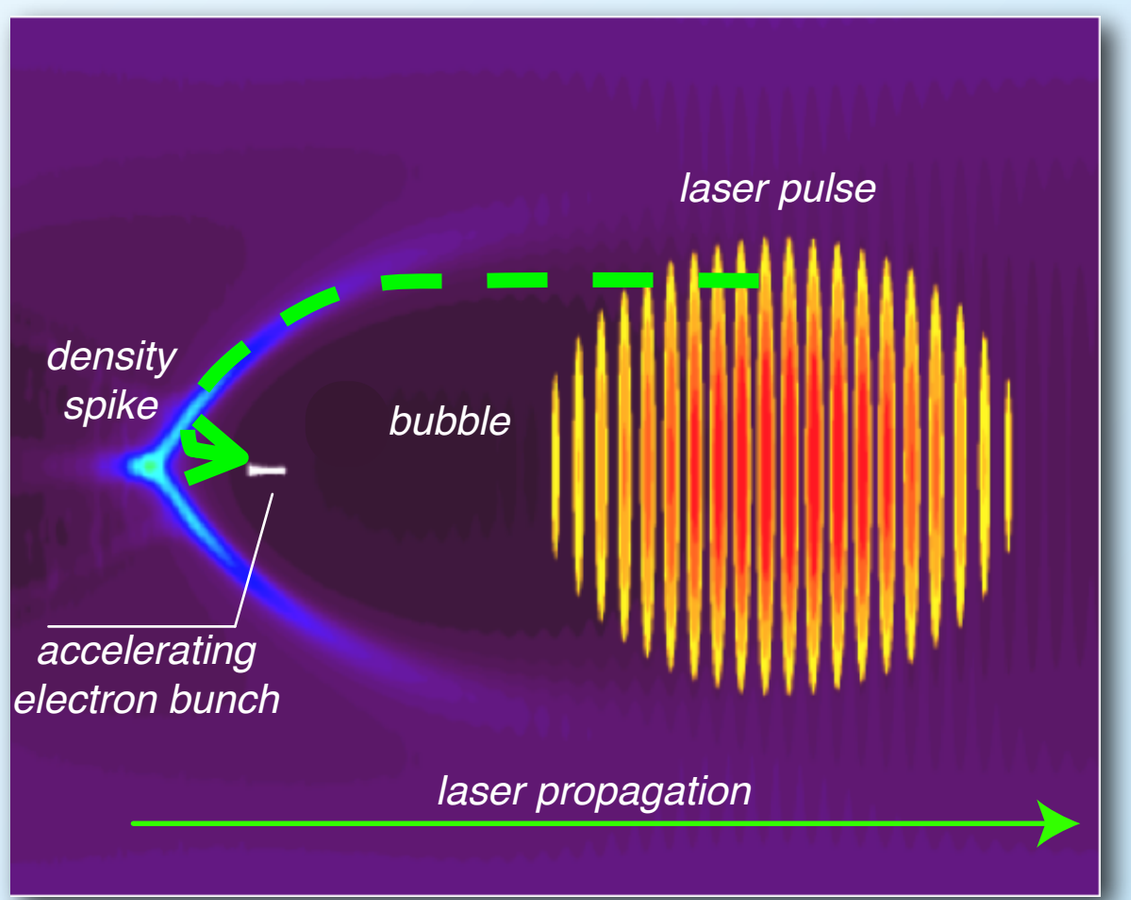
- Injection
- Staging

Leemans & Esarey, Physics Today, March 2009; C.B. Schroeder et al., PRST-AB 13 (2010)

Background Plasma Electrons can be Self-Injected

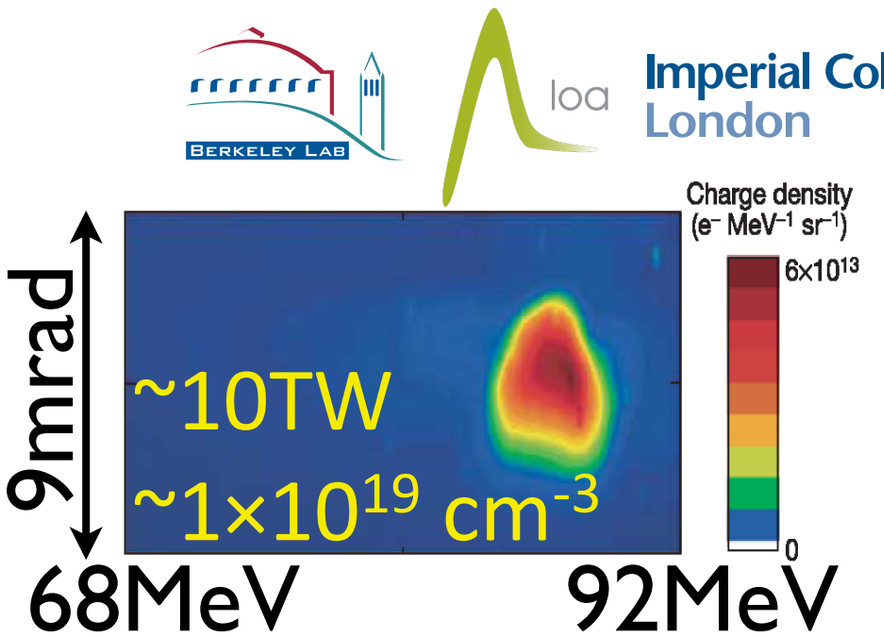


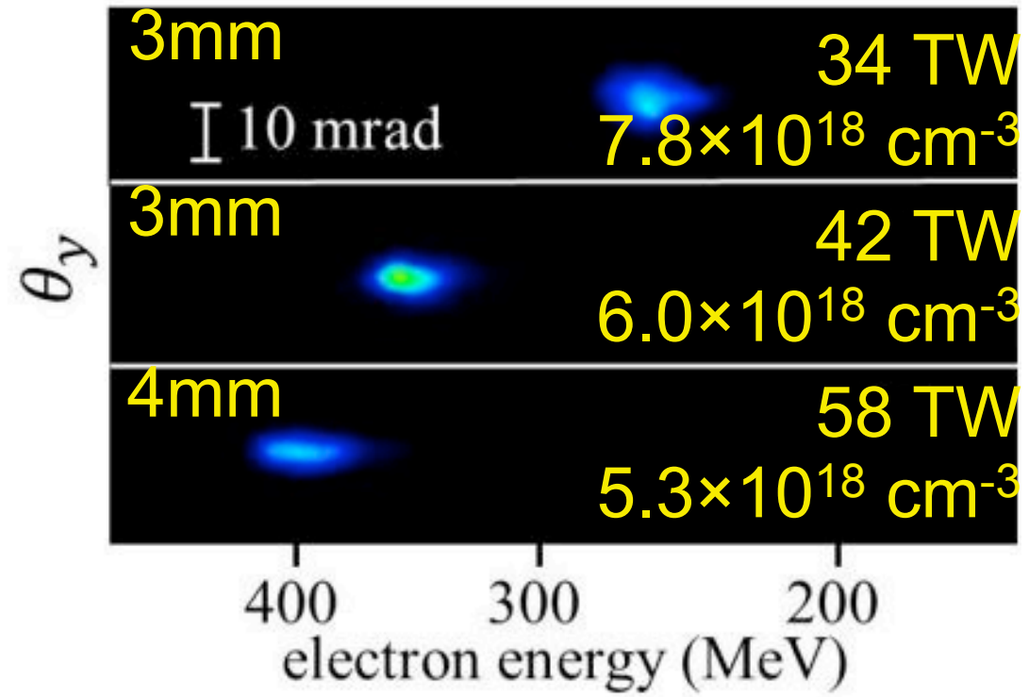


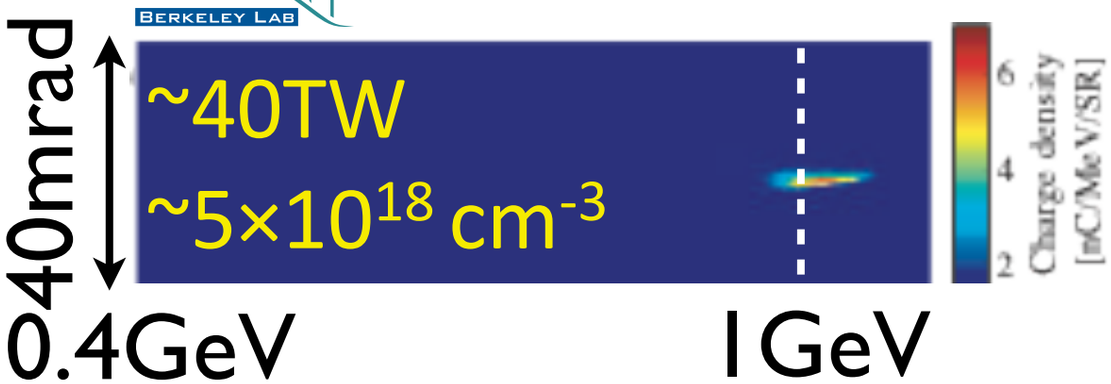


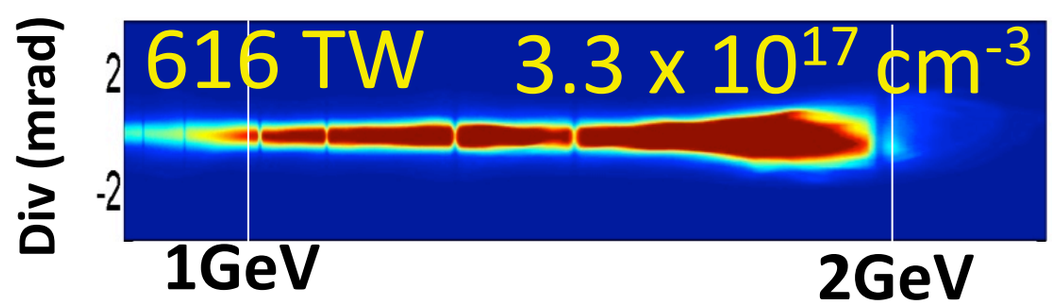
Lower Density and Higher Laser Power Increase Beam Energy

$$\text{Energy Gain} = E_0 L_{acc} \propto \frac{I}{n_e}$$









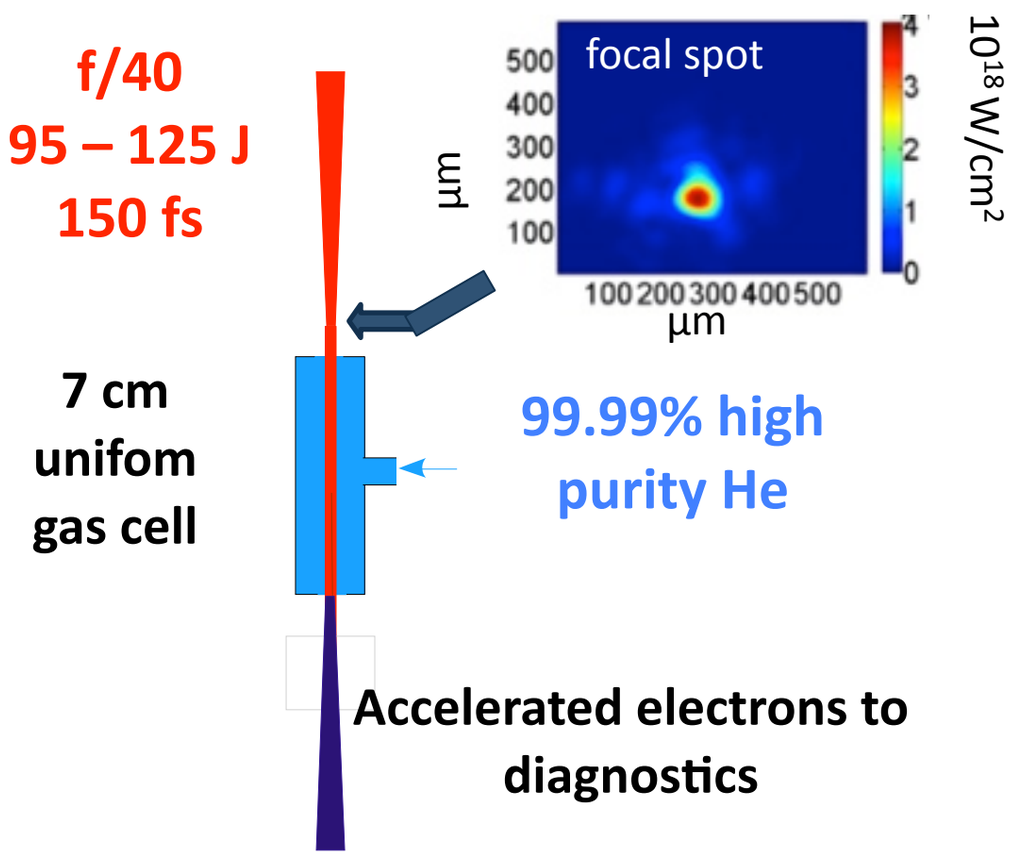
talk X. Wang WG 1

C. G. R. Geddes,et al, Nature,**431**, p538 (2004); S. Mangles et al., Nature **431**, p535 (2004); J. Faure et al., Nature **431**, p541 (2004); Leemans et al., Nature Phys. **2**, 696–699 (2006); Banerjee et al., Phys. Plasmas **19**, 056703 (2012); X. Wang et al., in press (2012).

Self-injected LWFA was observed down to n_e= 10^{17} cm^{-3} at the Texas Petawatt Laser

(> 2 GeV electrons produced)

Experimental setup

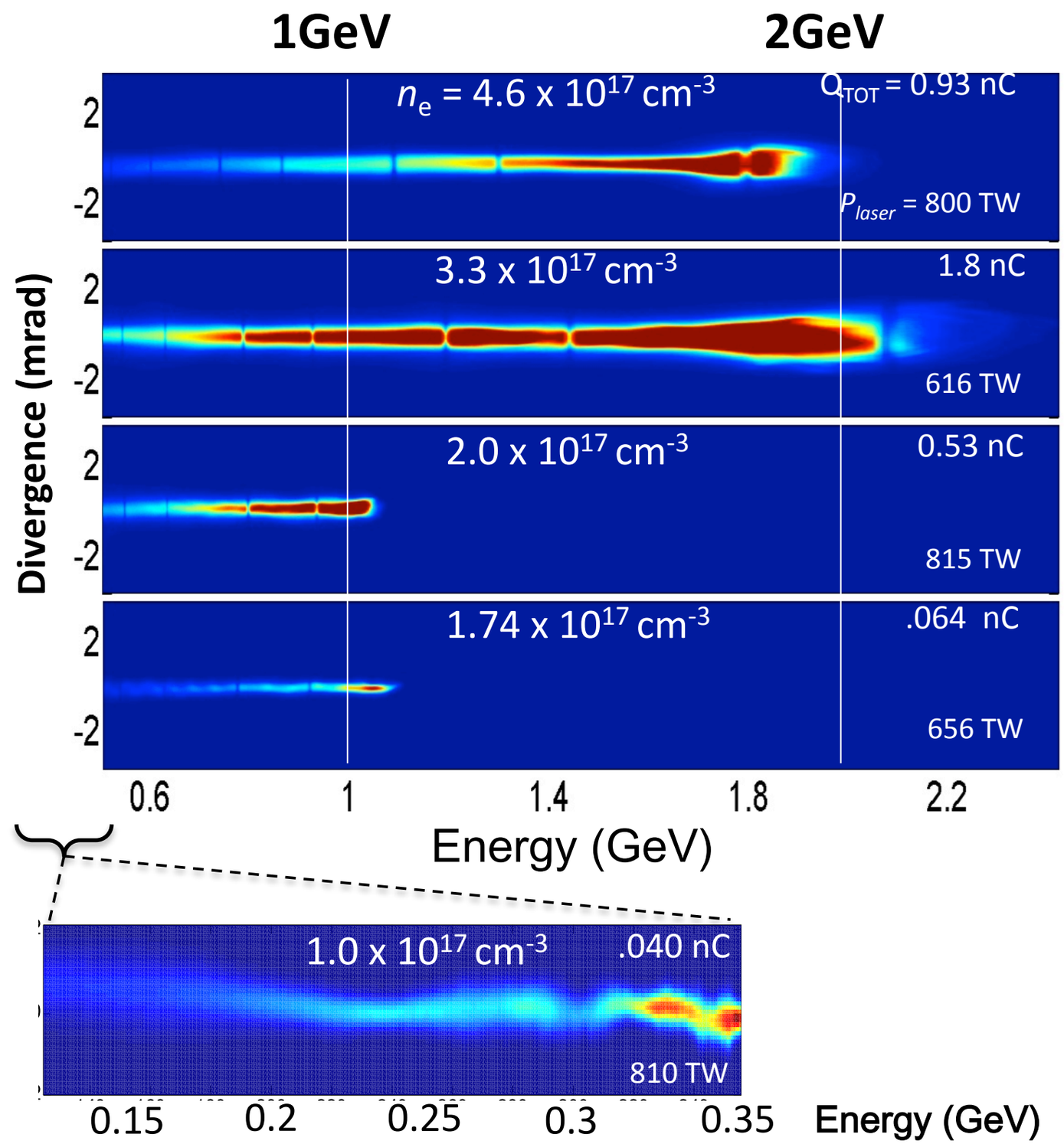


- Self trapping highlights (different expts)
  - MultiGeV (Texas PW)
  - 1/4 mrad divergence (Texas PW)
  - ~1% energy spread (several groups)
  - 0.1 mm-mrad norm. emittance*

X. Wang et al., J. Plasma Phys., in press (2012)

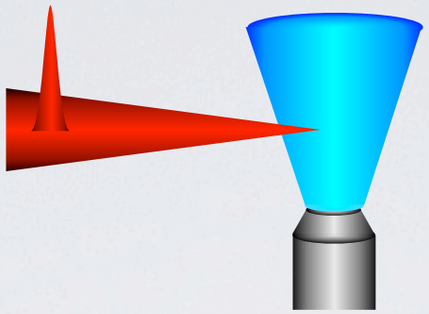
*Plateau et al., submitted

Electron energy spectra

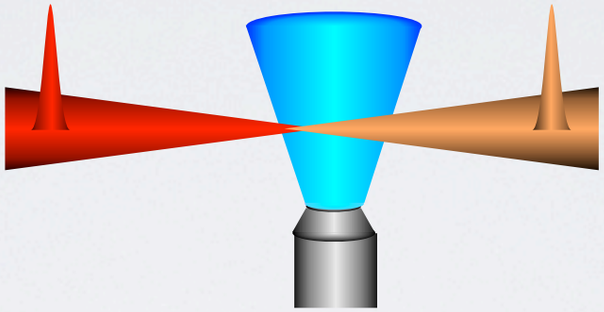


Several Methods of Controlled Injection being Developed

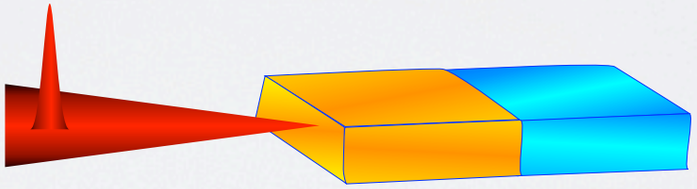
- External Injection



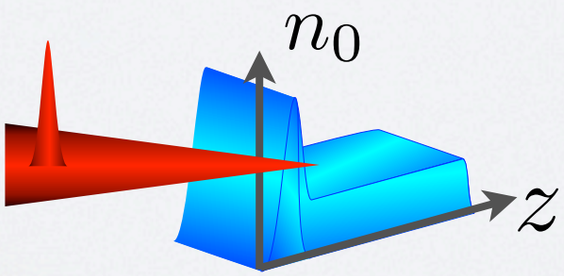
- Colliding pulse



- Ionization

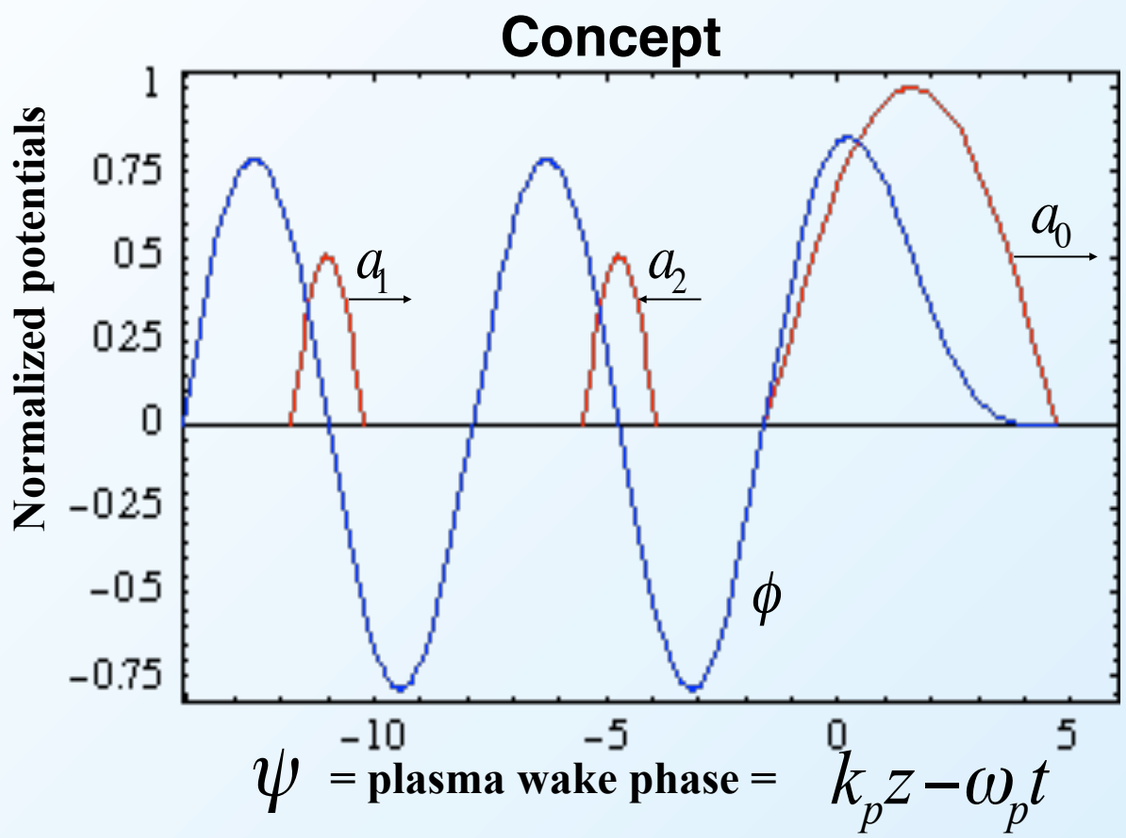


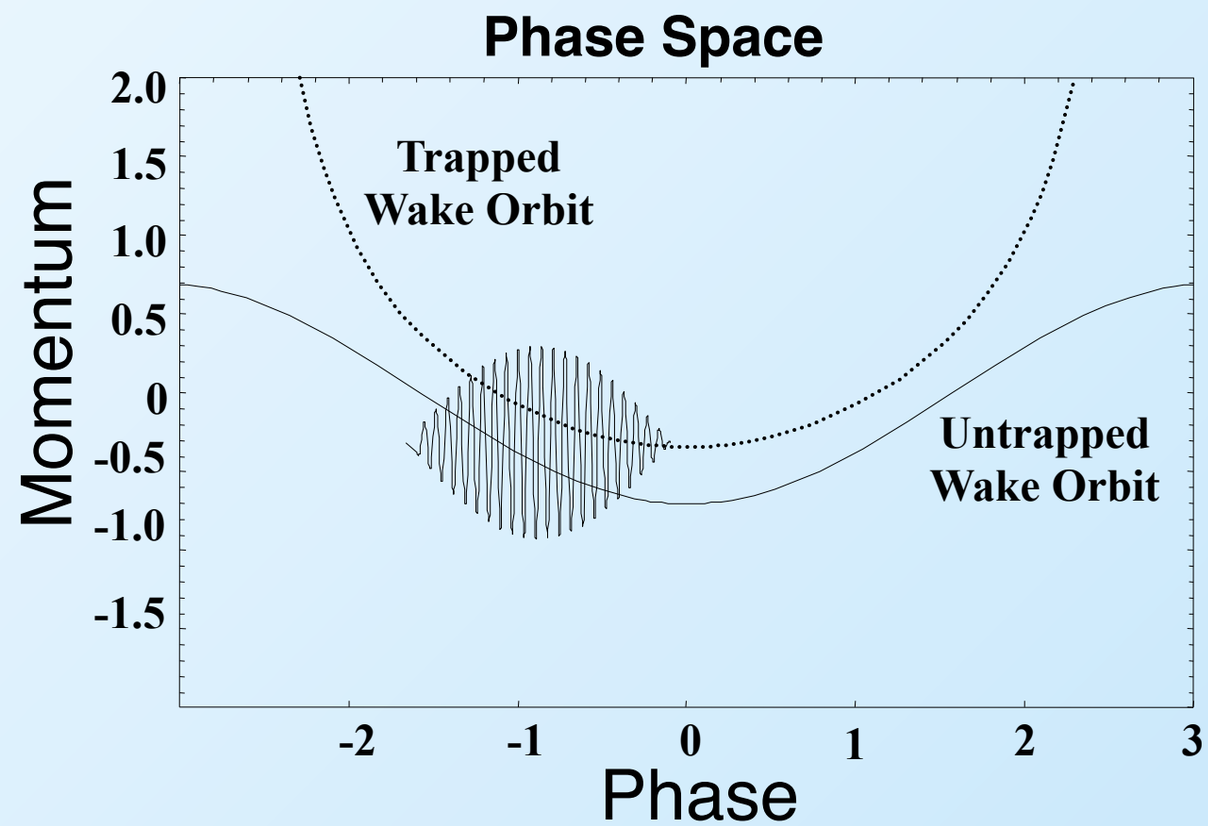
- Density tailoring

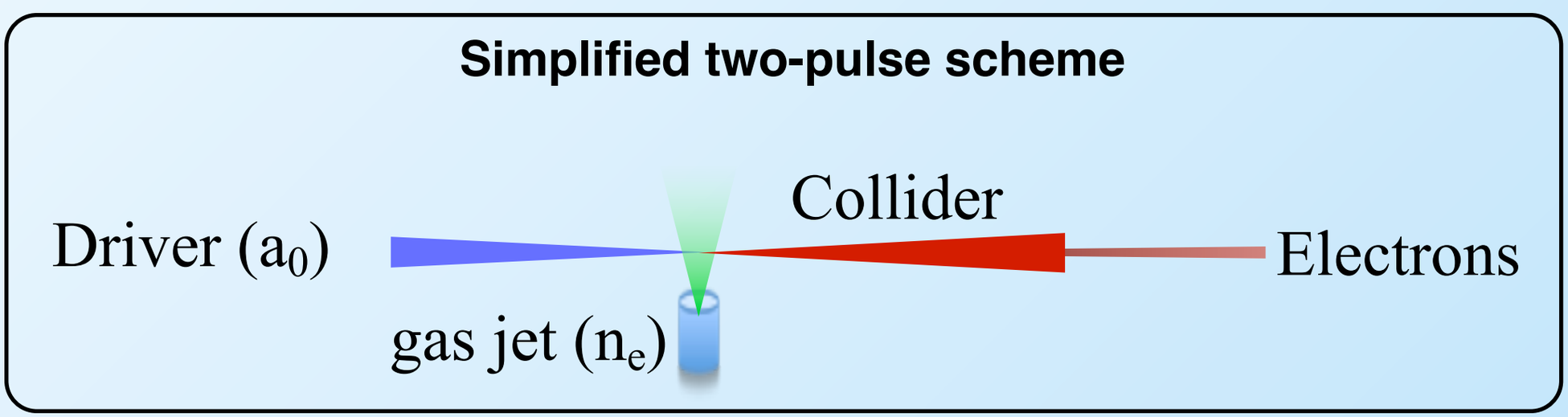


Colliding Pulse Injection

Slow Beat Wave Of Colliding Pulses Can Give Plasma Electrons Momentum Boost Into Trapped Orbit

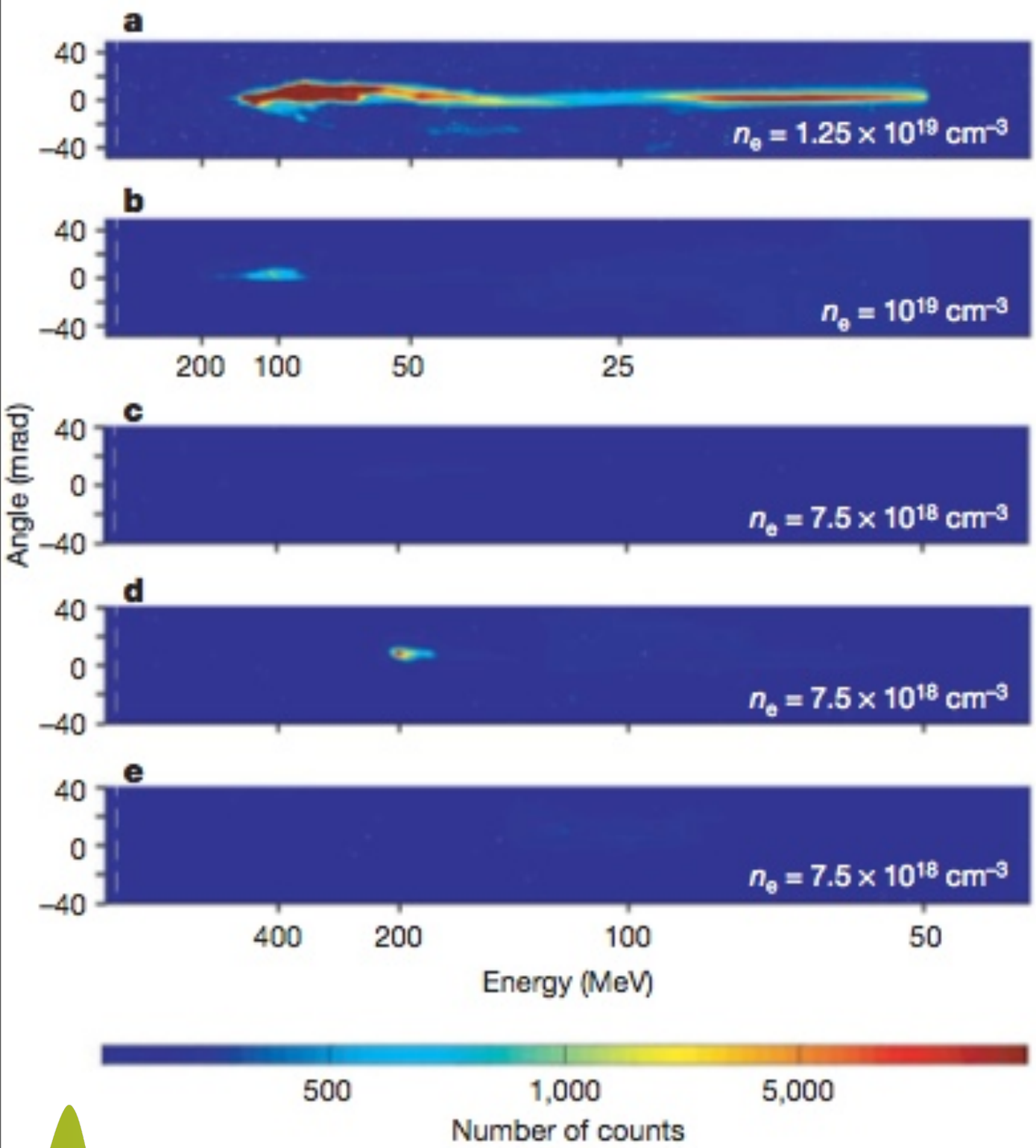




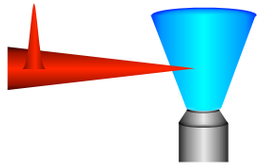


Esarey *et al.*, PRL (97); Schroeder *et al.*, PRE (99), Fubiani *et al.* PRE (04); J. Faure et al., Nature 444, (06)

Colliding Pulse Showed Injection At Low Density

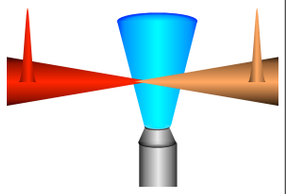


Single pulse injection at high density



Density too low for injection

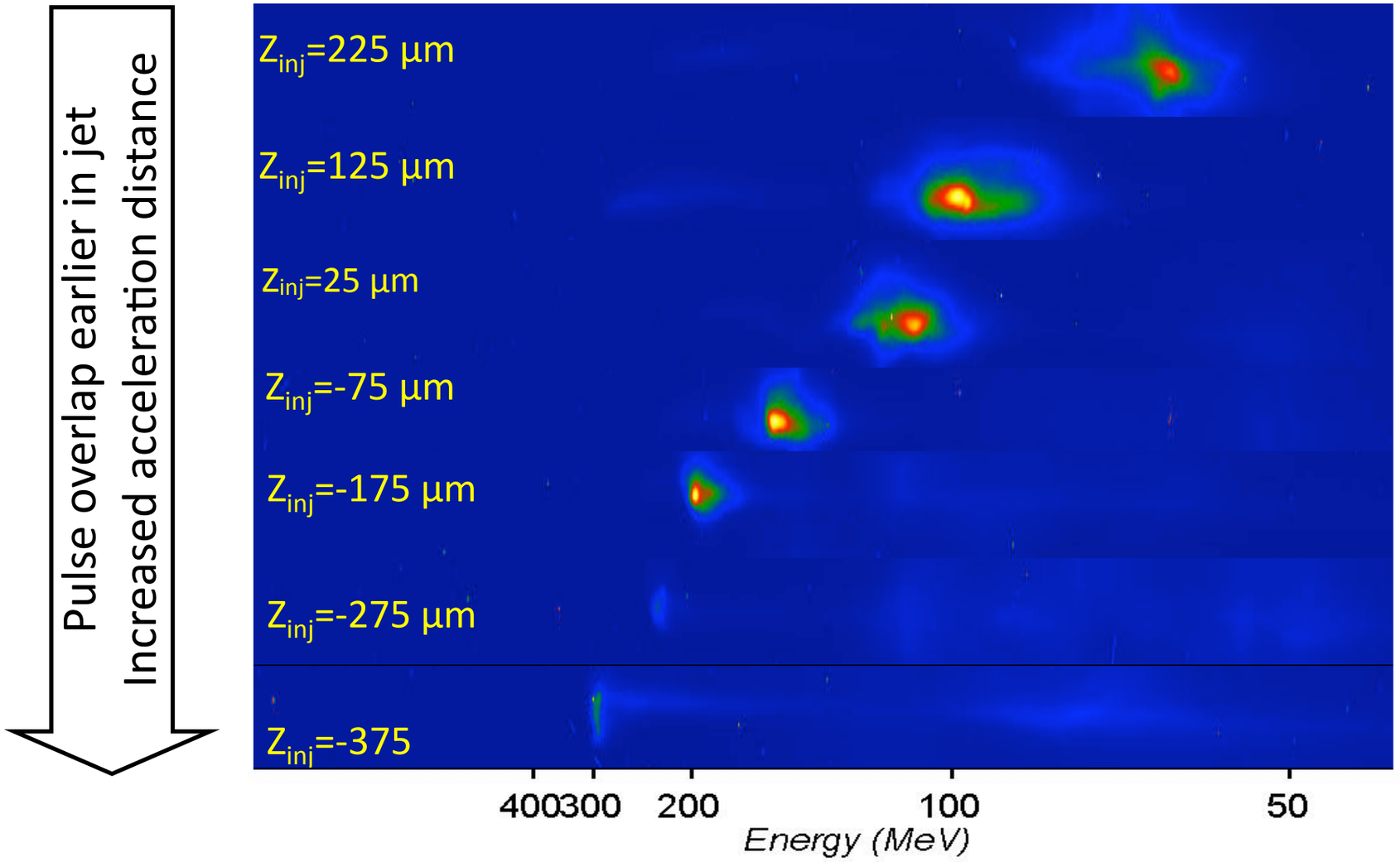
Colliding pulse enables injection

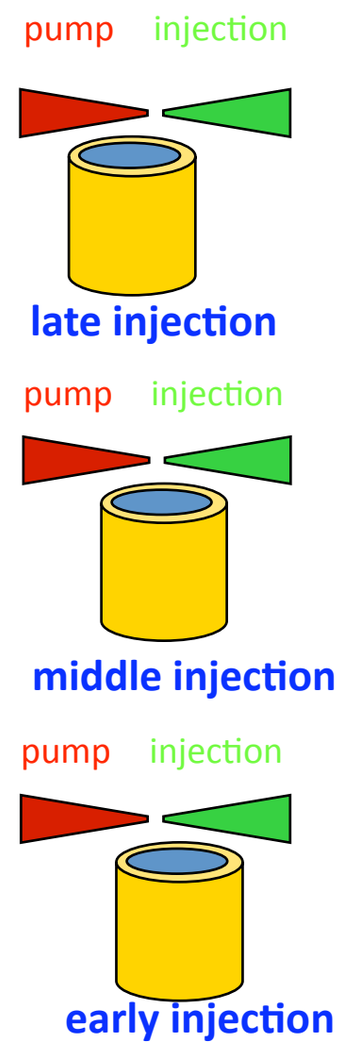


No injection for crossed polarization

J. Faure *et al.*, Nature **444**, 737 (2006)

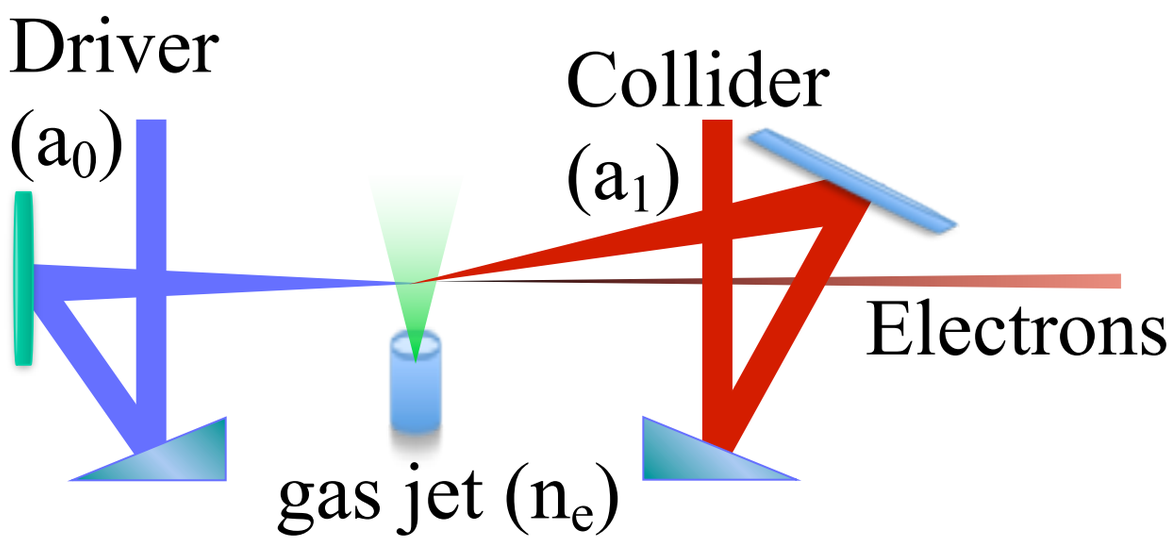
Location Of Pulse Overlap To Tune Beam Energy



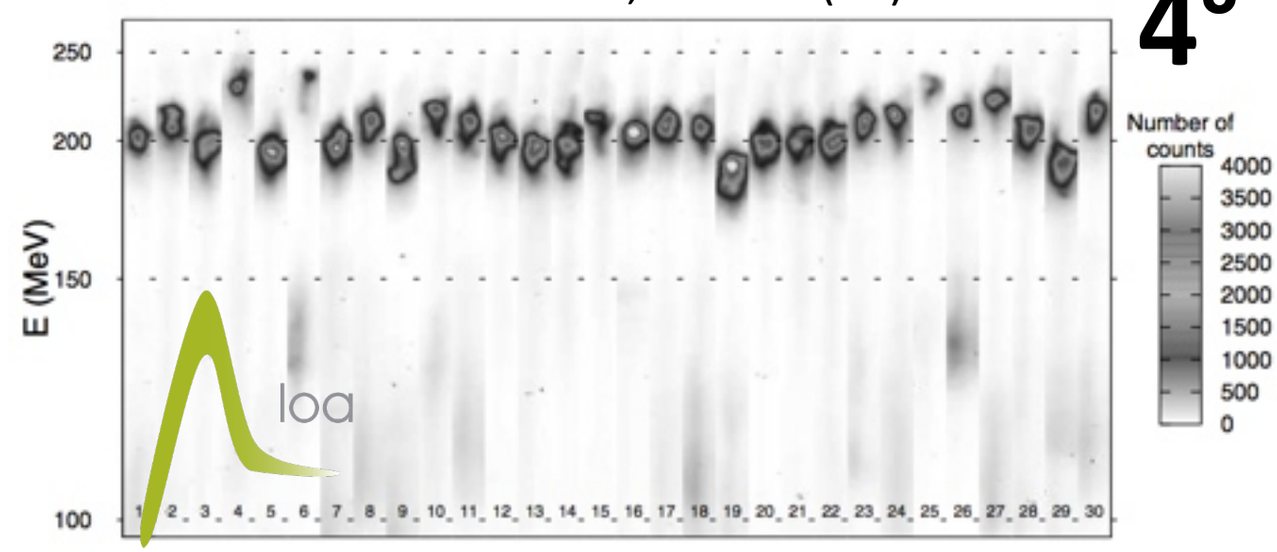


J. Faure *et al.*, Nature **444**, 737 (2006)

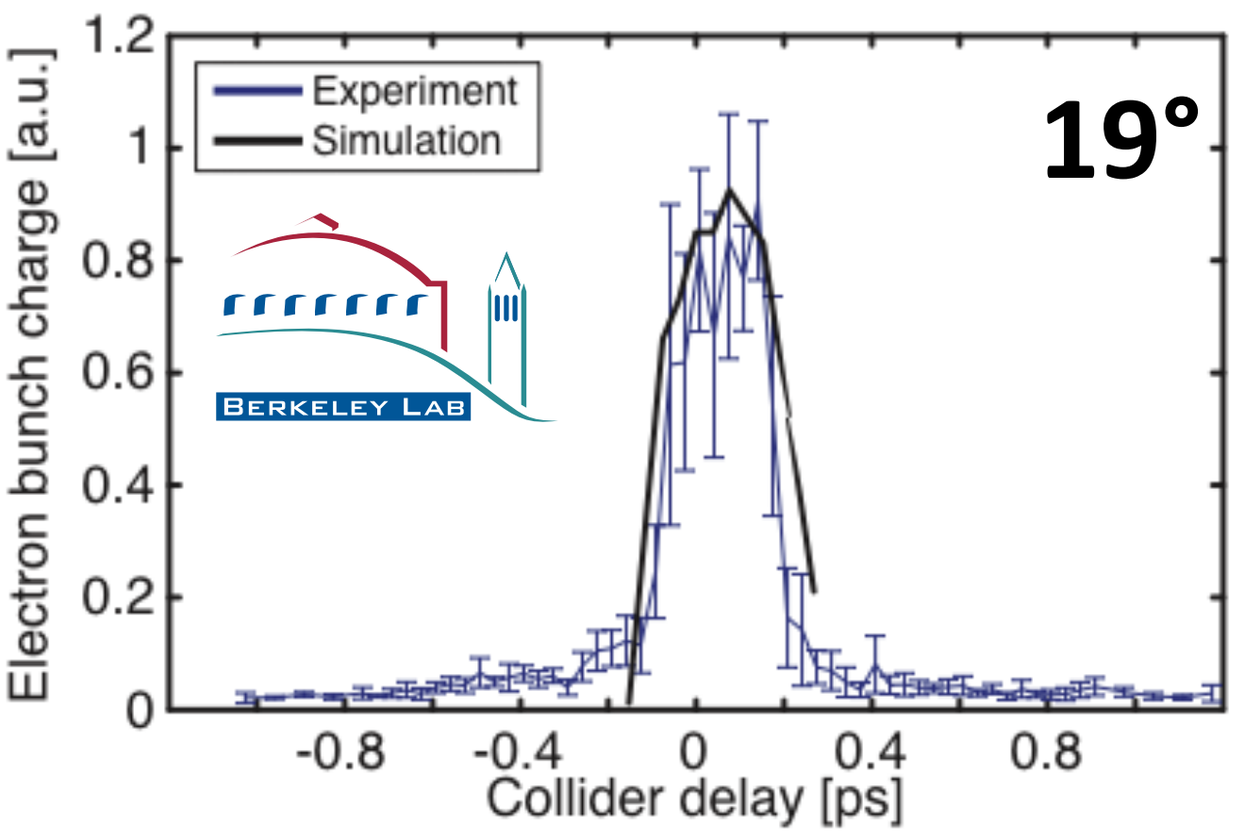
Colliding Pulse Injection Shown For Various Injector Angles

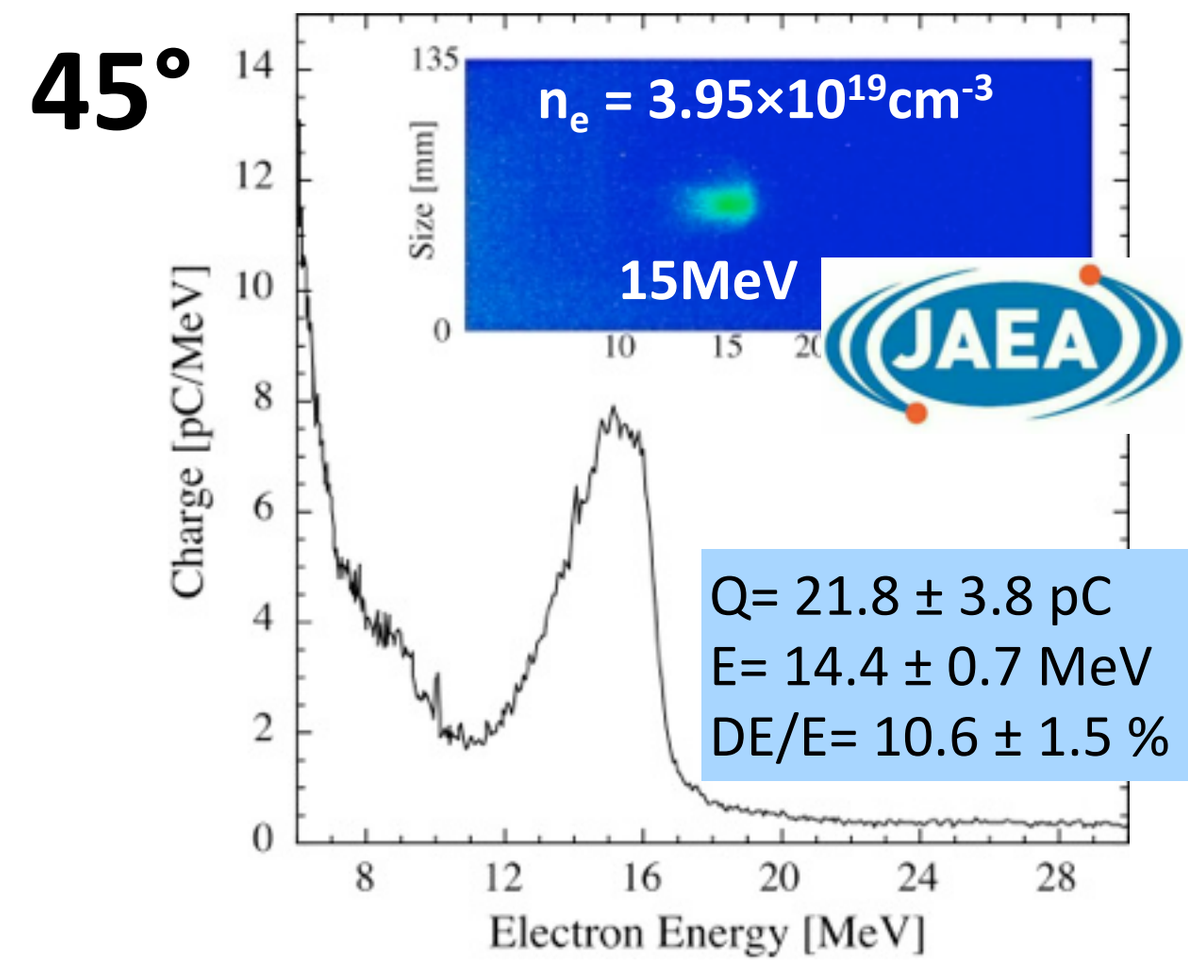


Malka et al., POP **16** (09)



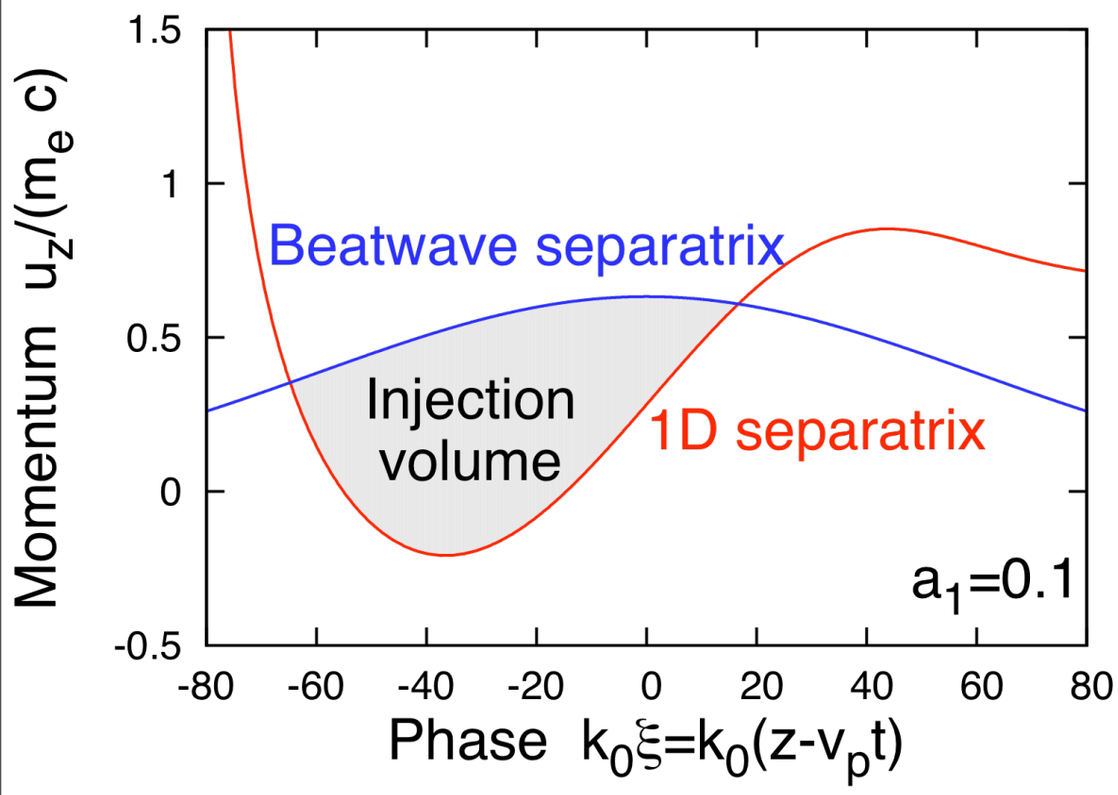
Nakamura et al., AAC 2004; Plateau et al. AAC 2010

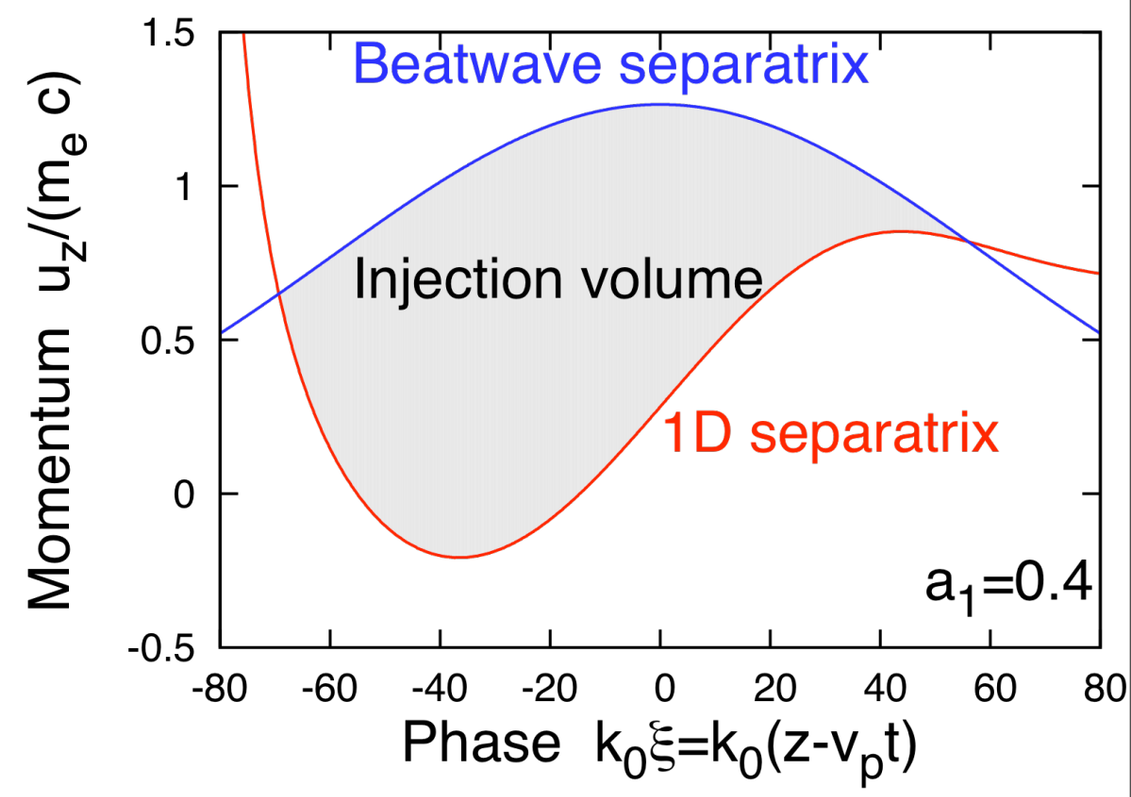


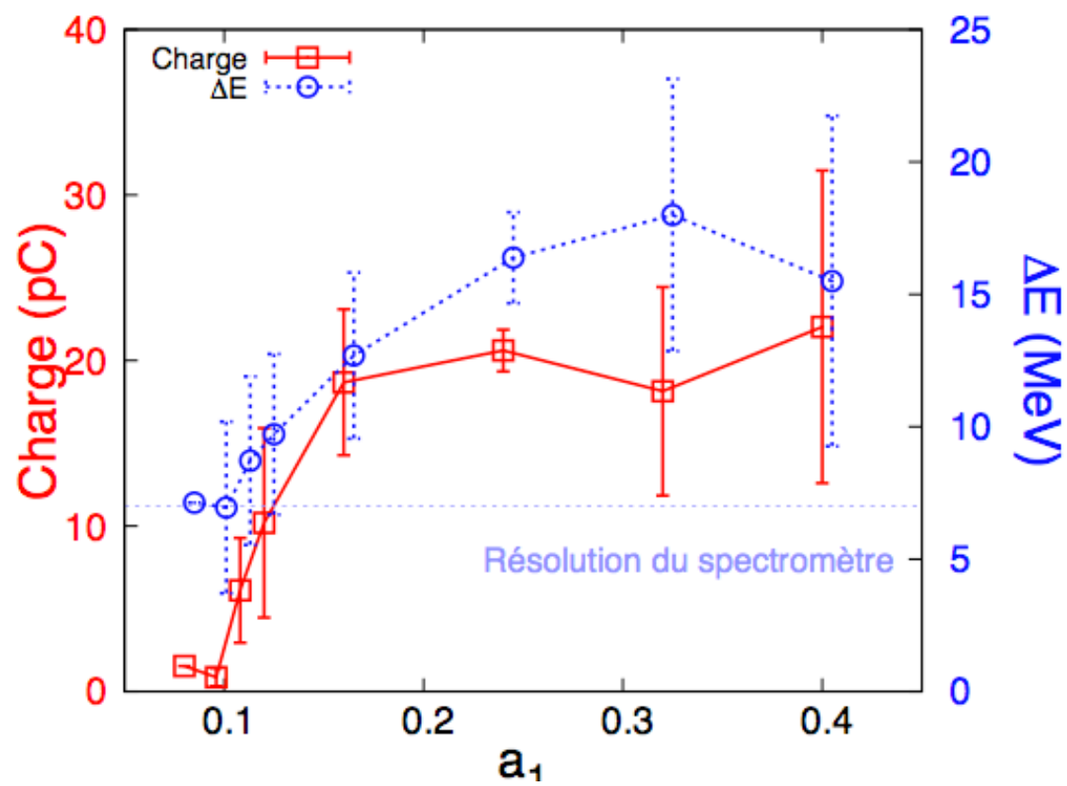


H. Kotaki, et al., Phys. Rev. Lett. **103**, (09)

Charge Increased At The Expense Of Energy Spread By Tuning Injection Laser Intensity

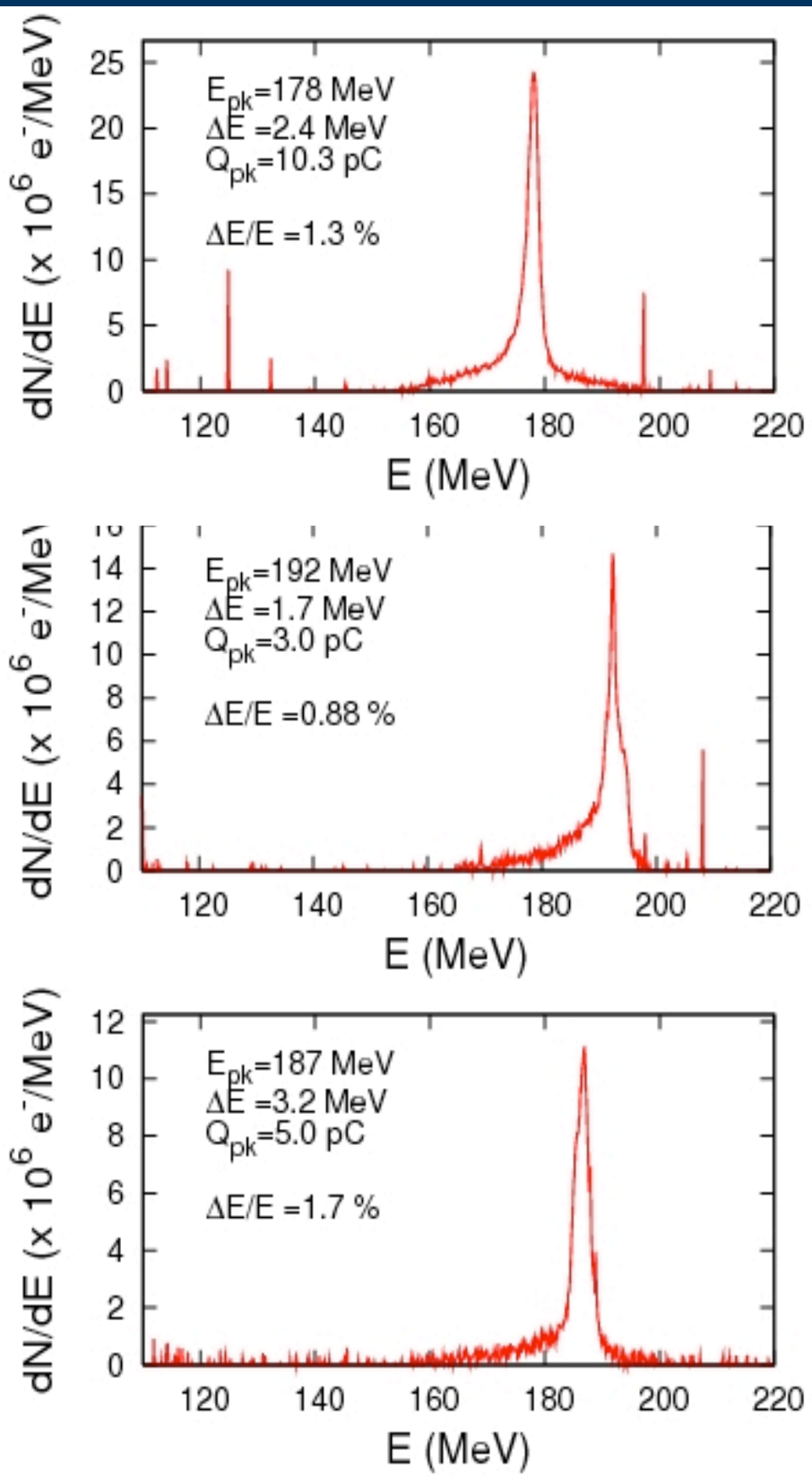




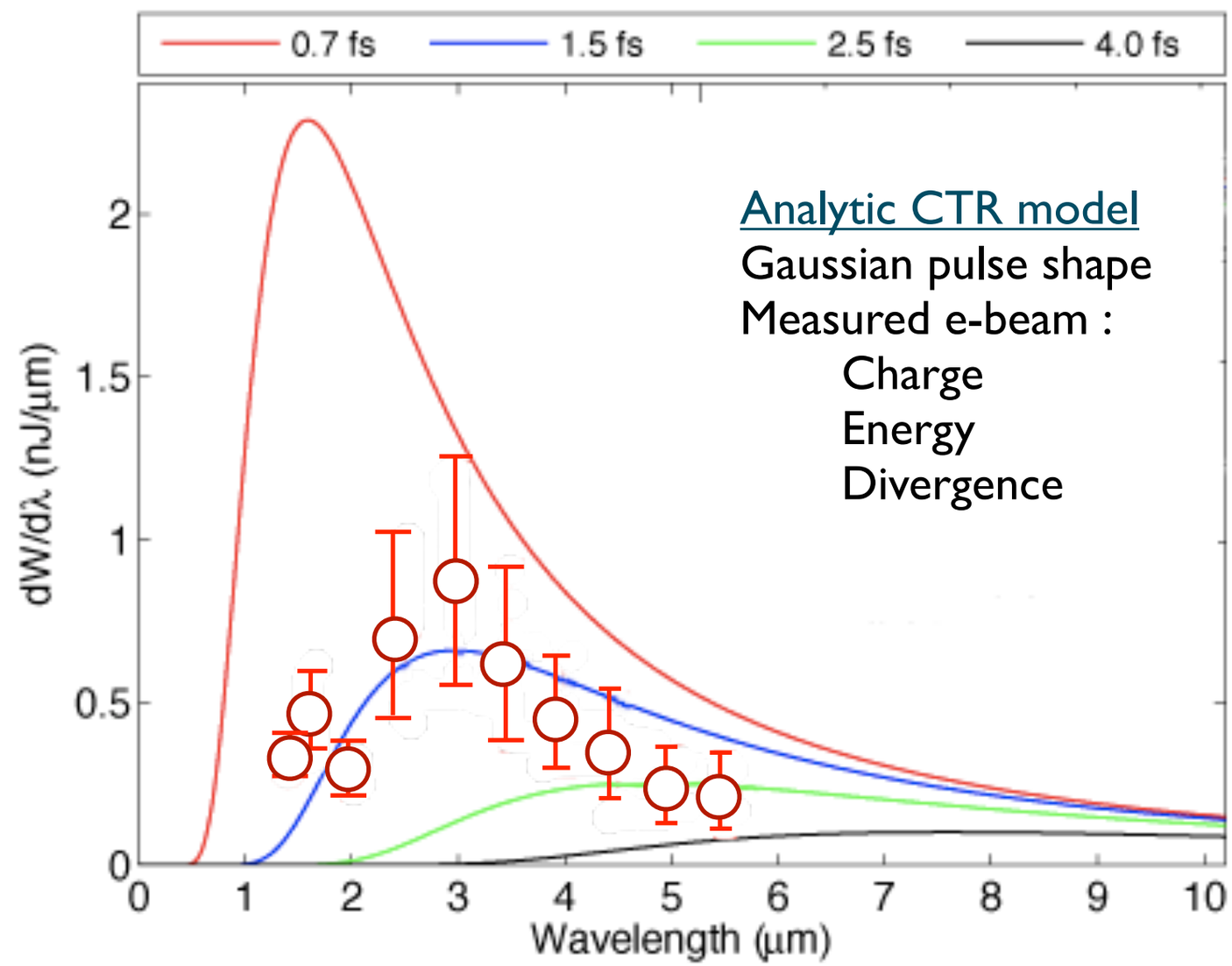


C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

Colliding Pulse Shown To Produce Energy Spread As Low As 1% And fs Beams



CTR shows 1.5 fs RMS duration
→Peak current 4 kA

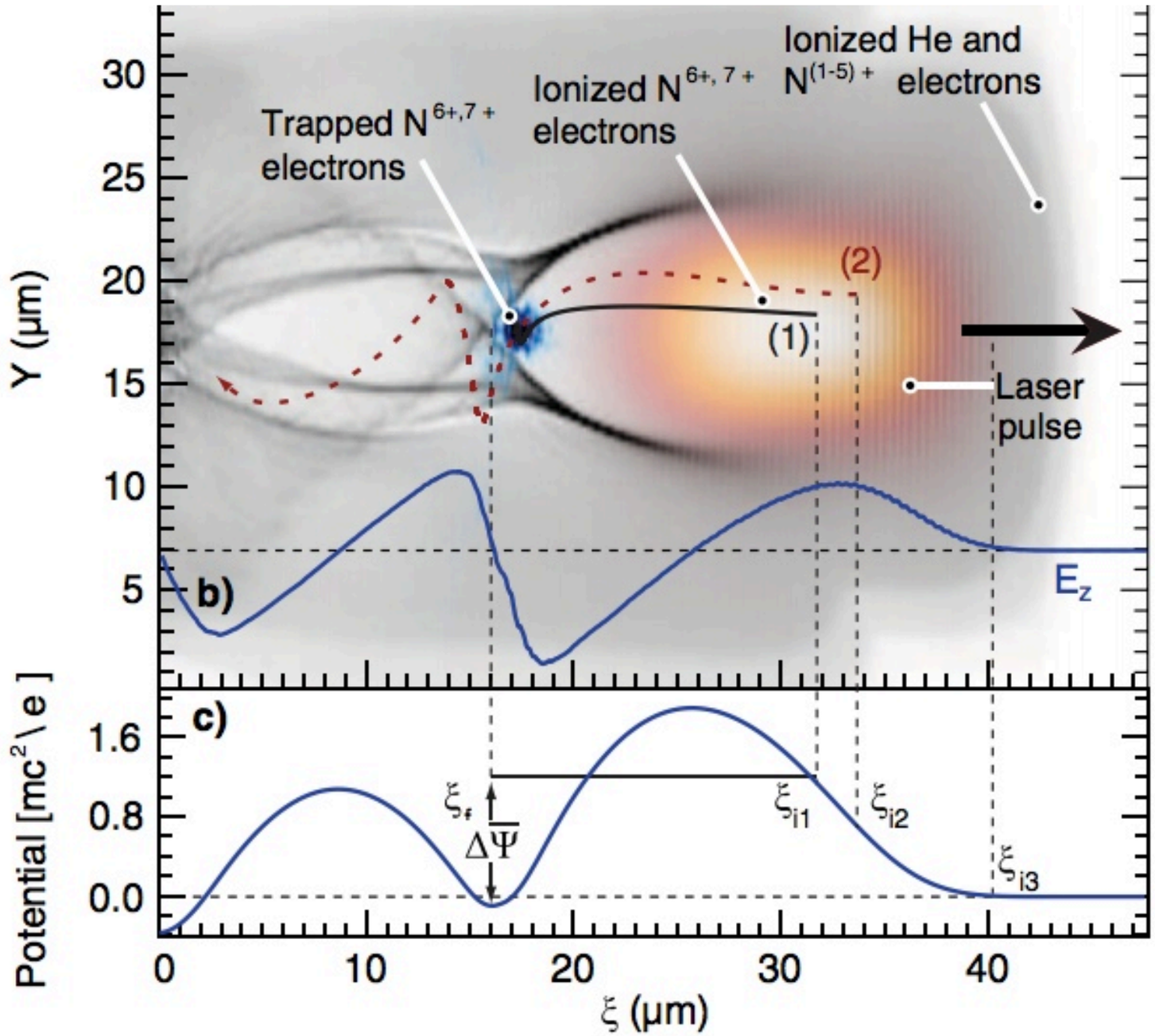


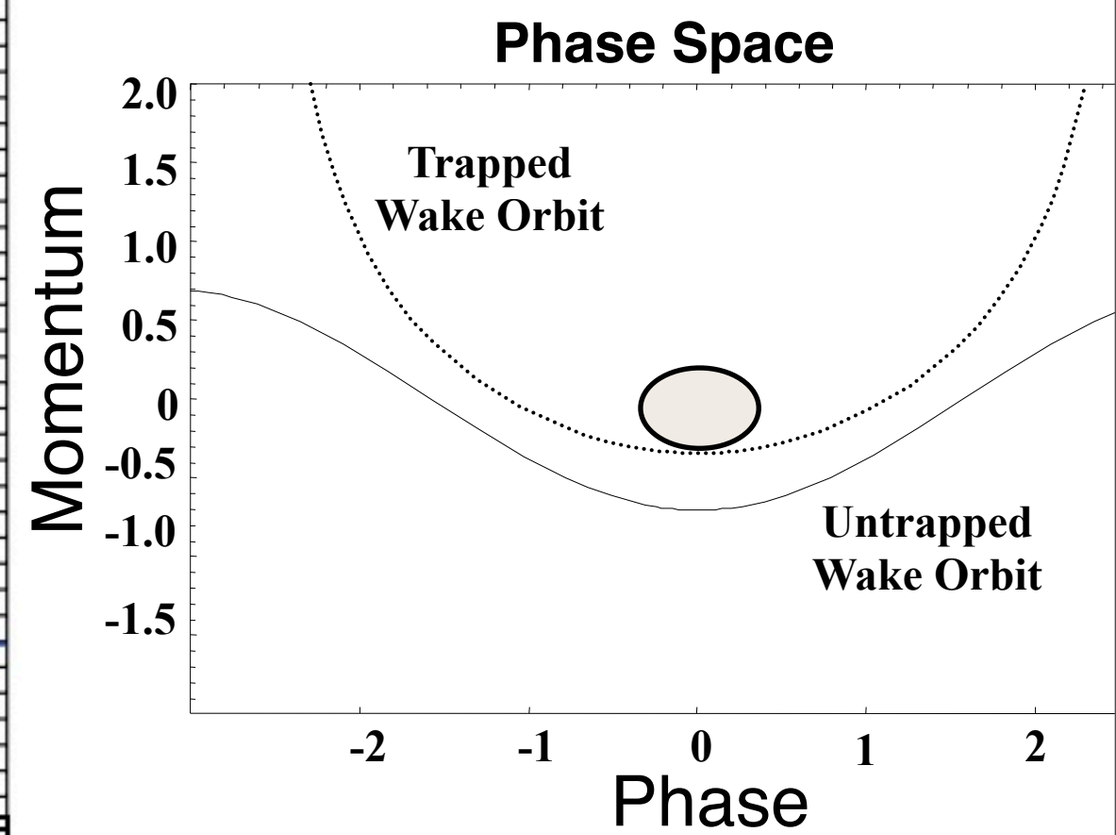
C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009); O. Lundh et al., Nature Physics, **7** (2011)

Ionization

Injection

Ionization At The Peak Of The Laser Pulse Places Electrons At Correct Phase To Be Injected

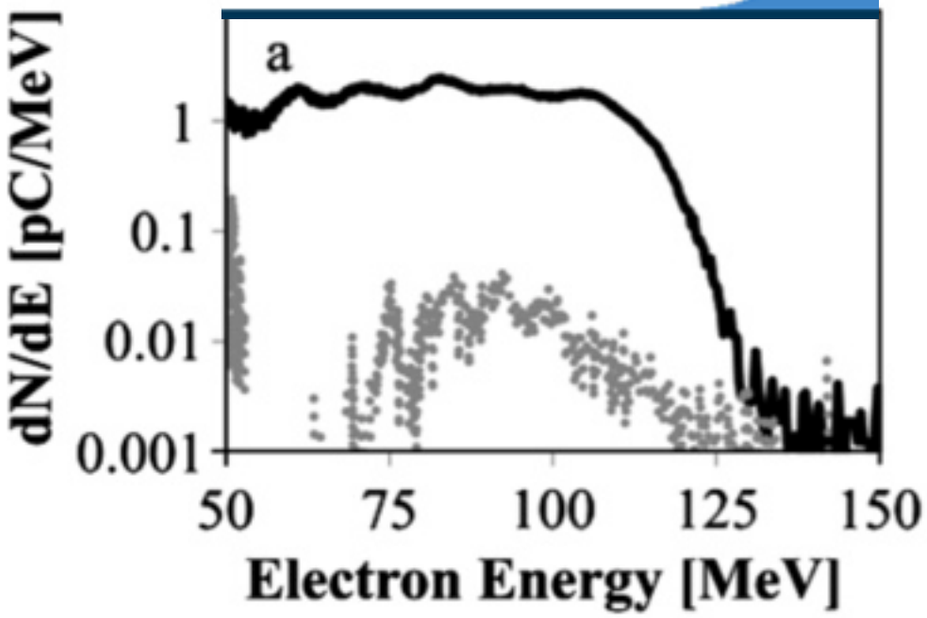


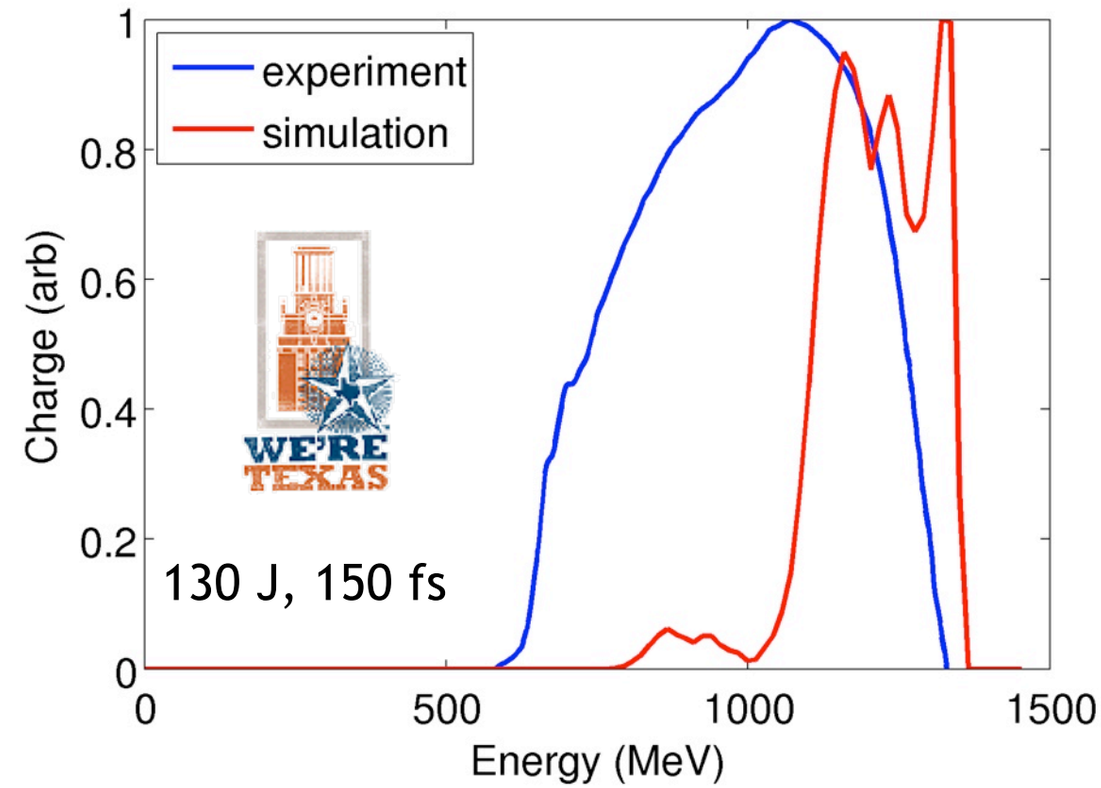


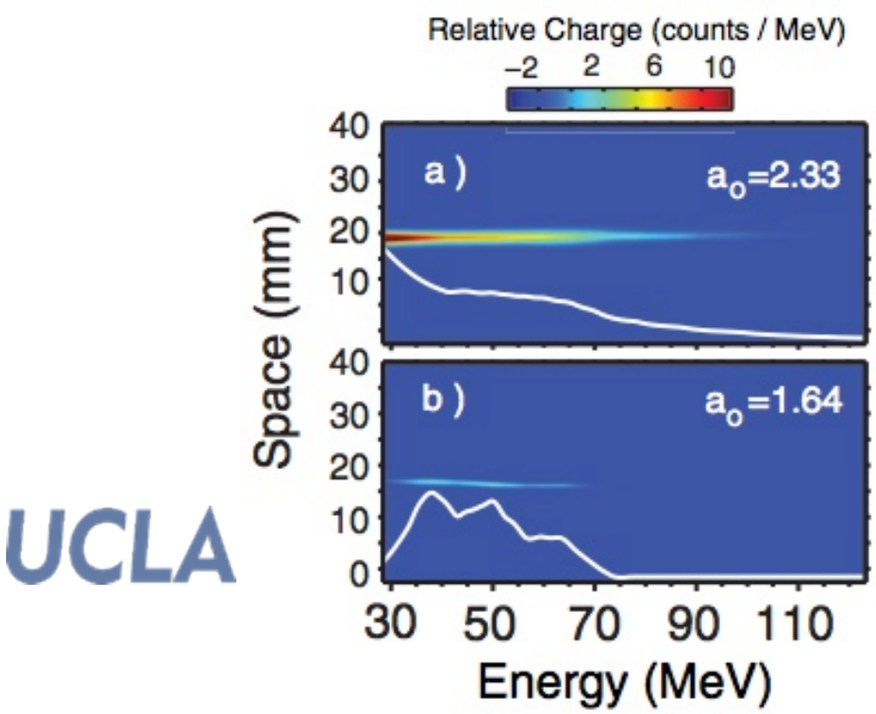
First seen in expts by Oxford University

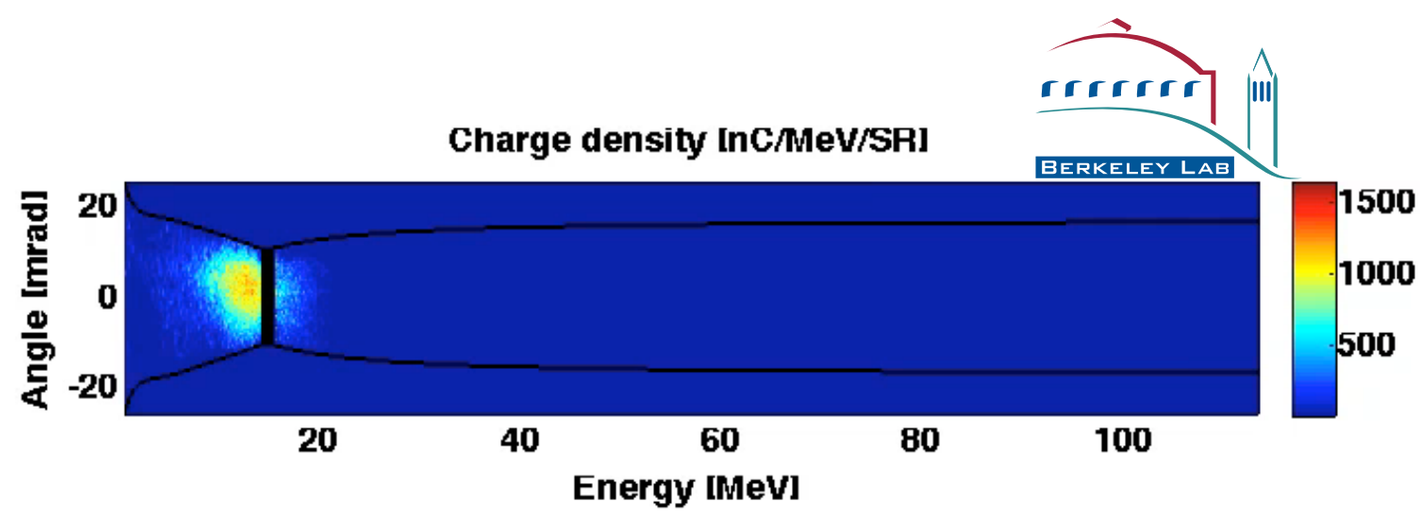
M. Chen et al., JAP **99** (06), T. Rowlands-Rees et al., PRL **100** (08) Pak et al., PRL **104**, (10); C. McGuffey et al., Phys. Rev. Lett. **104**, (10)

Ionization Injection Demonstrated By Several Groups



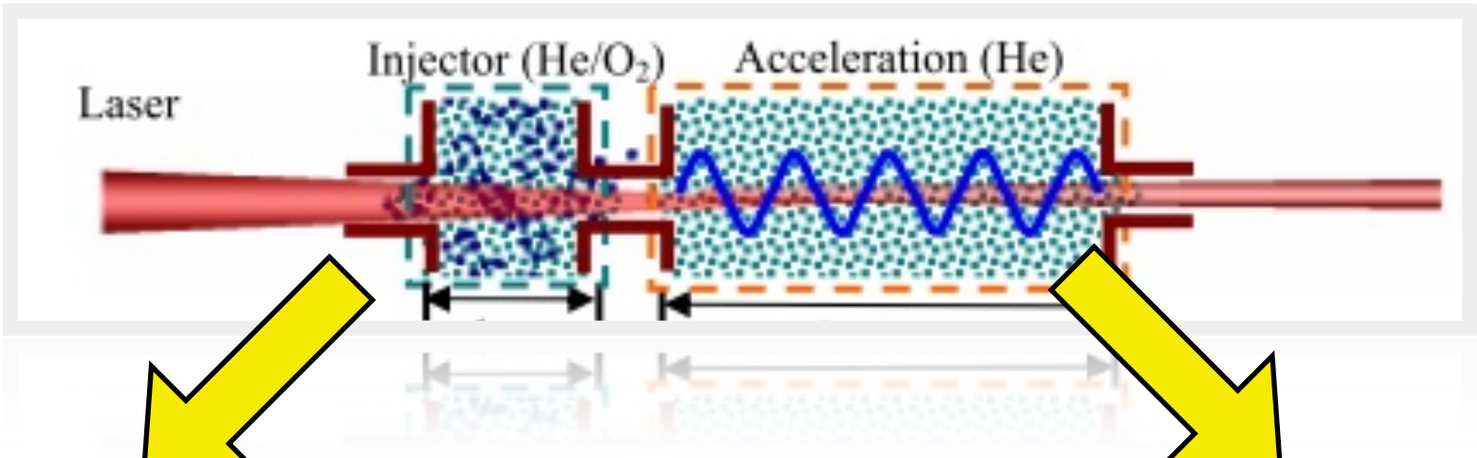






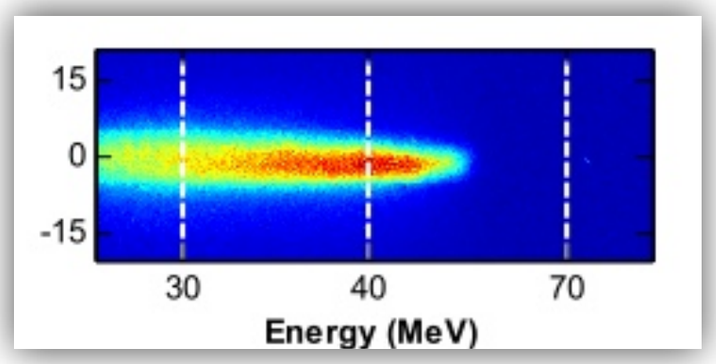
Pak et al.; PRL **104**, (10); C. McGuffey et al.; PRL. **104**, (10); talk by X. Wang

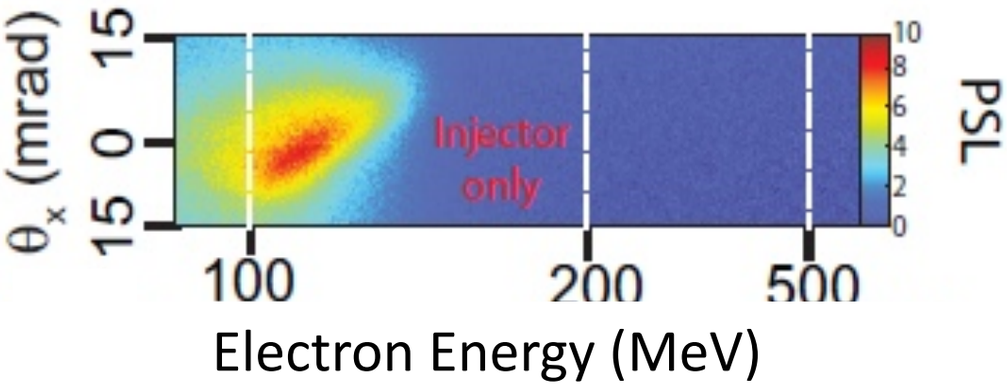
Energy Spread Reduced by mixed gas injector & pure He accelerator



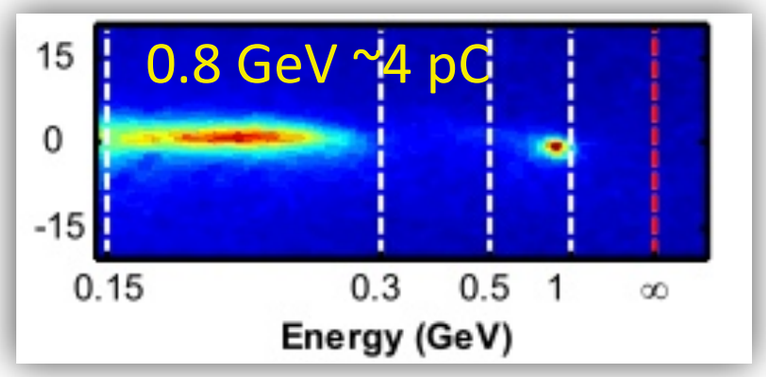
boxes around vertica
injector text above b
acc text/...

Injector

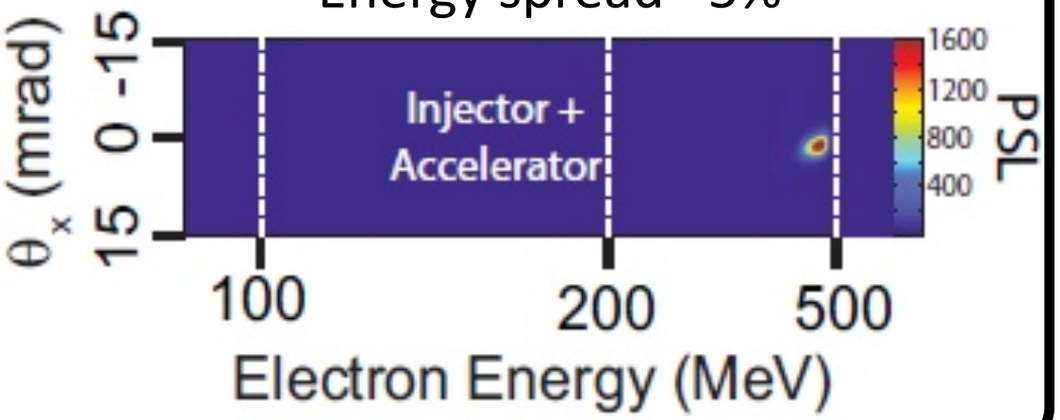




Injector+Accelerator



Energy spread ~5%



J.S. Liu et al., Phys. Rev. Lett. 107, 035001 (2011); B.B. Pollock et.al., PRL 107, 045001 (2011)
Talk by J.S. Liu WG1; Talk by B. Pollock

Injection by Density tailoring

Phase Velocity And Trapping Is Controlled Via Plasma Density Gradients

Trapping when plasma wave amplitude high and phase velocity low

plasma wave phase velocity controlled by longitudinally tailoring plasma wavelength

$$\beta_p = \frac{\omega}{ck} = \beta_g \left(1 + |\zeta| \frac{1}{\lambda_p} \frac{d\lambda_p}{dz}\right)^{-1}$$

λ_p

Snapshots of the plasma density as the laser propagates

$d\lambda_p/dz > 0$

Trapping enabled

$d\lambda_p/dz < 0$

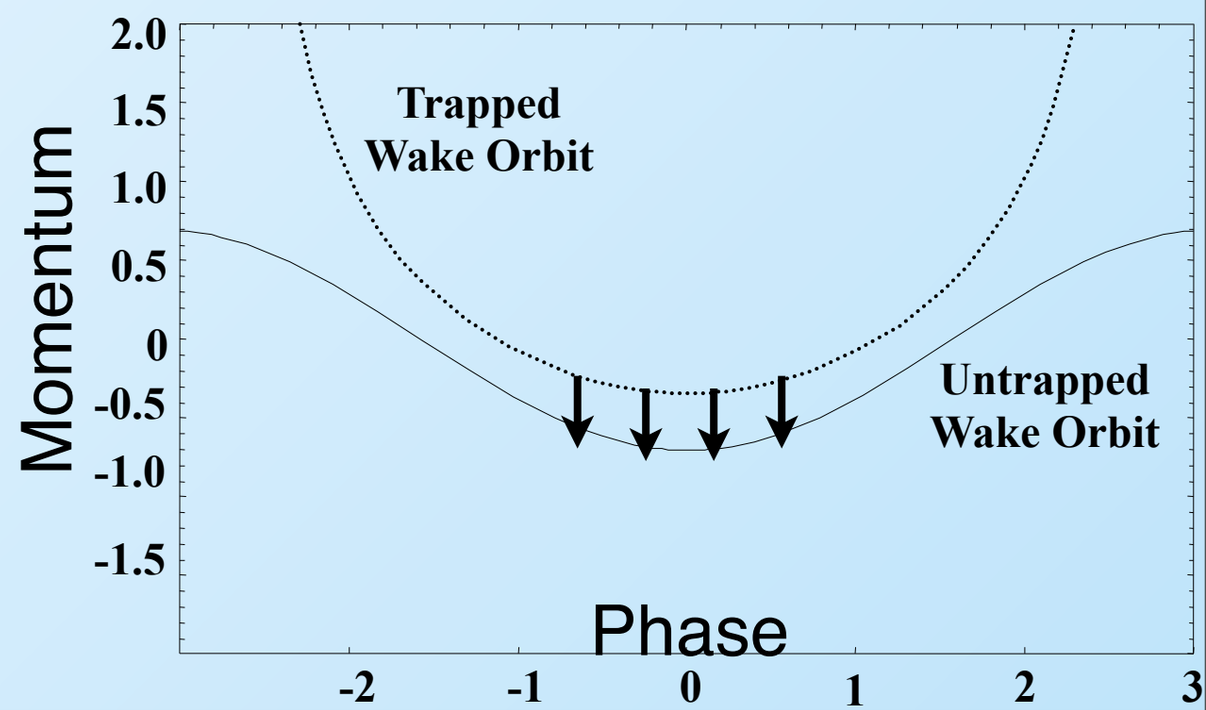
Trapping terminated

Phase velocity can be reduced by

- Negative plasma density gradient
  - Theory: Bulanov et al. PRL 1997
  - Experiment: Geddes et al., PRL 2008

$$dn_e/dz < 0 \Rightarrow d\lambda_p/dz > 0$$

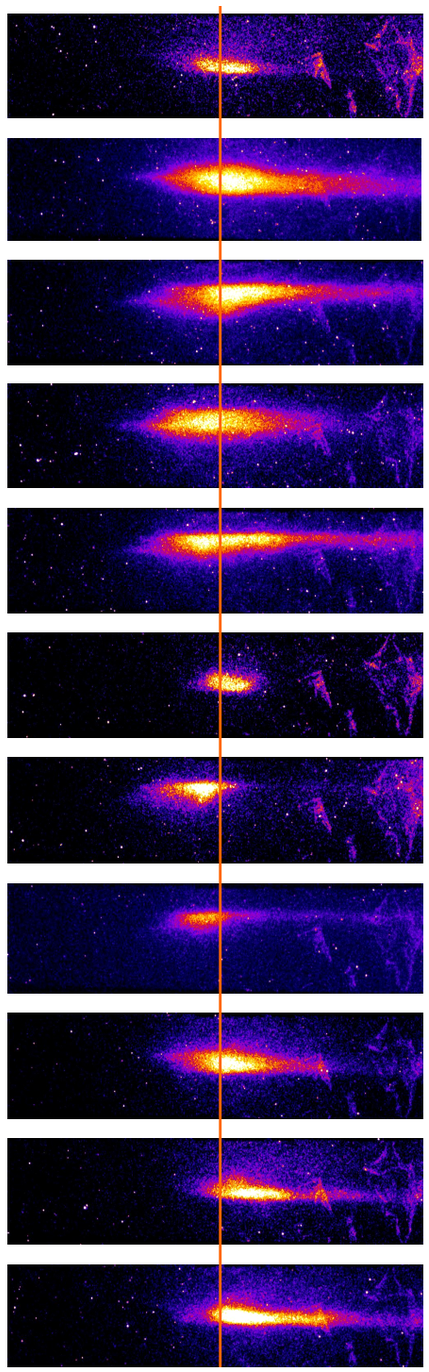
Since $\lambda_p \propto \frac{1}{\sqrt{n_e}}$

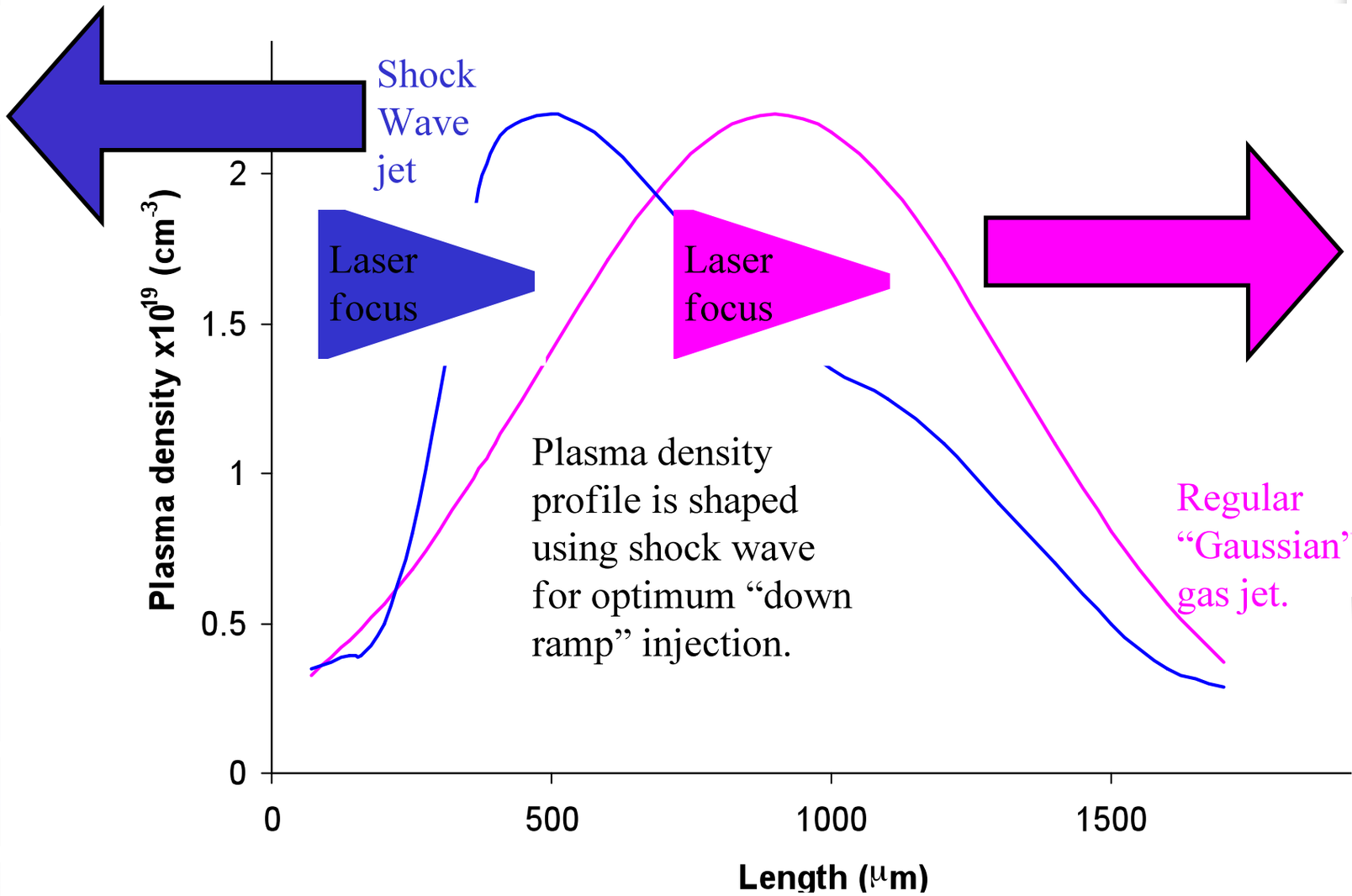


Down-ramp Injection Beam Energy Increased With Shockwave Jet

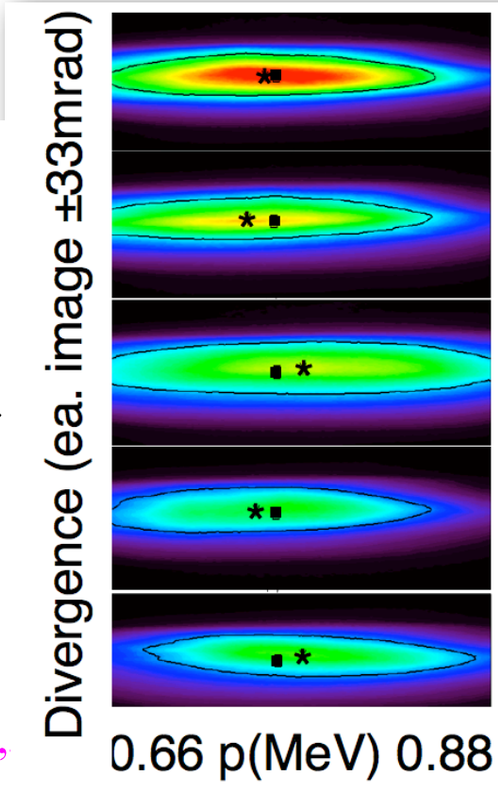
NRL Plasma Physics Division

40MeV





~1MeV

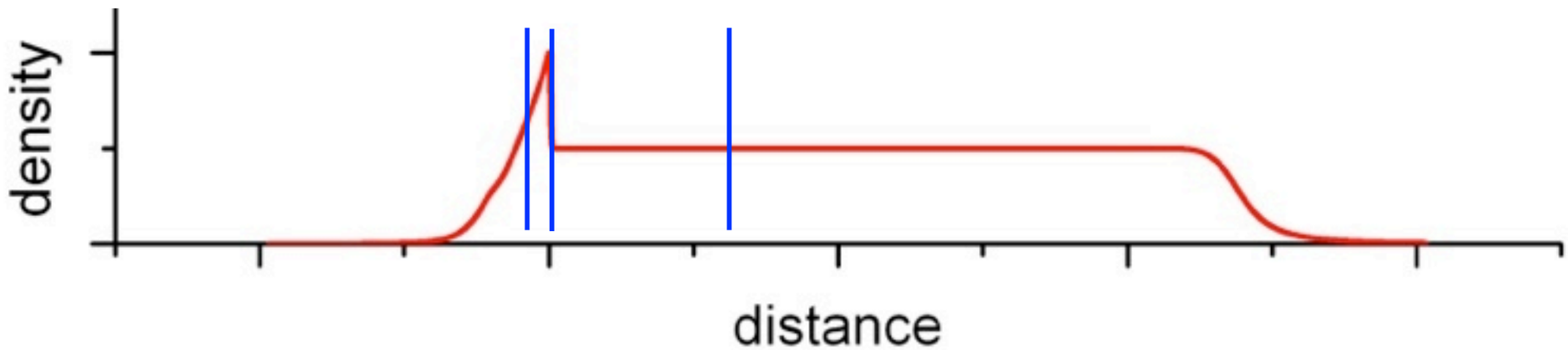


Phys. Rev. Lett. 045004 101 (08)

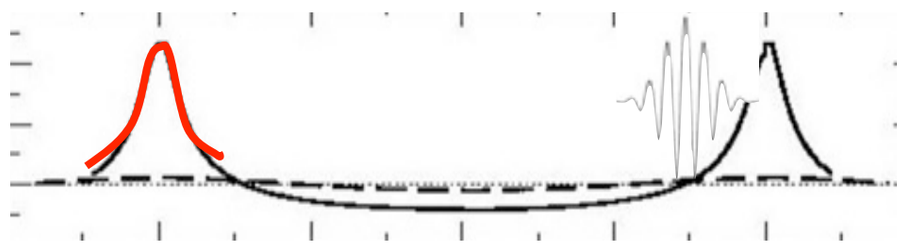
see talk D Kaganovich Today (afternoon WG1)

Phys. Rev. Lett. 105 (10); Appl. Phys. Lett. 97 (10); Phys. Plasmas 18 120701 (11)

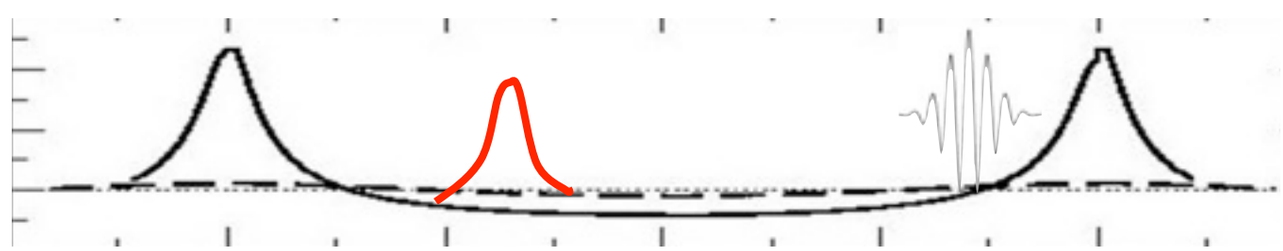
Sharper downramp can inject without transverse wavebreaking



Electron Density

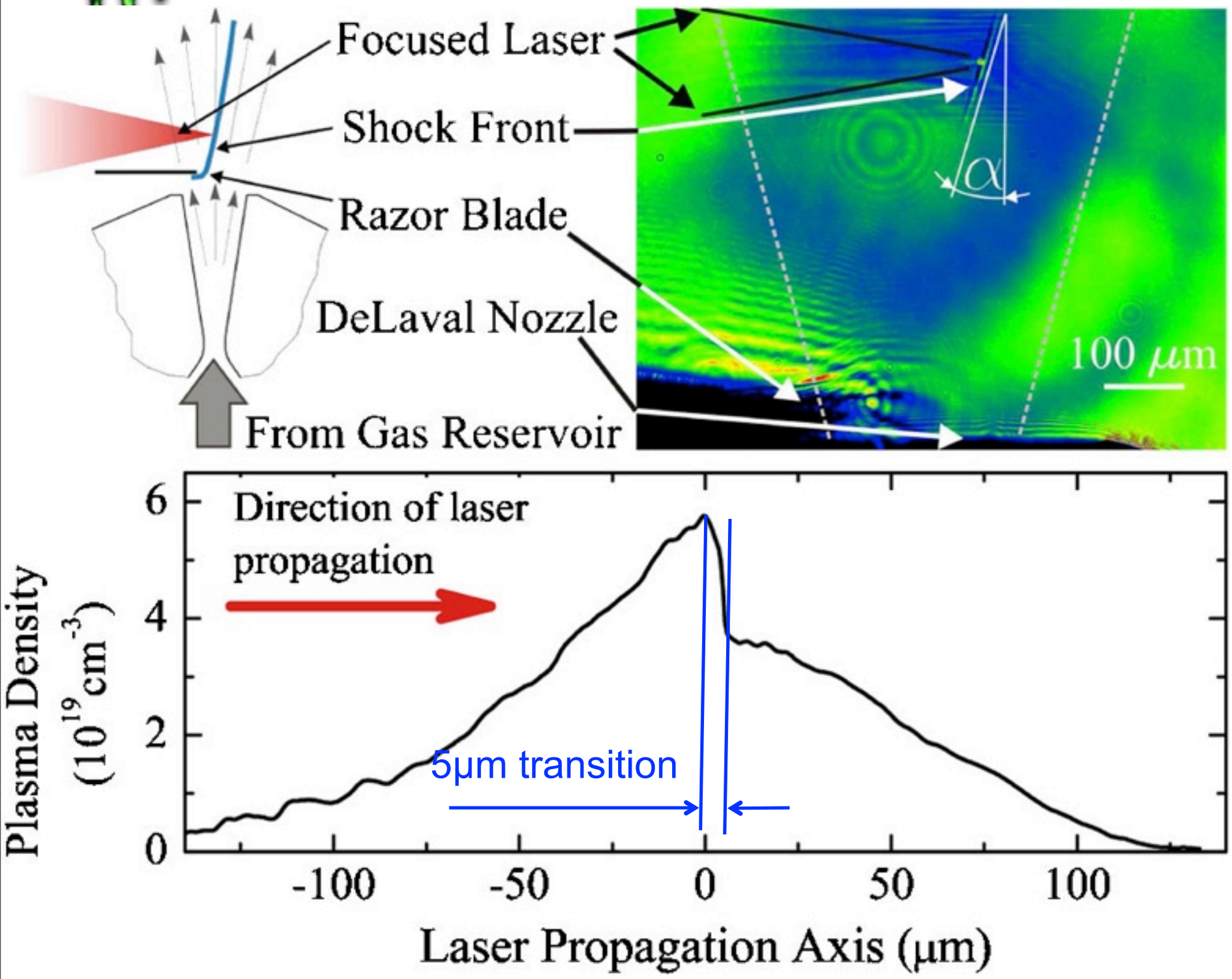


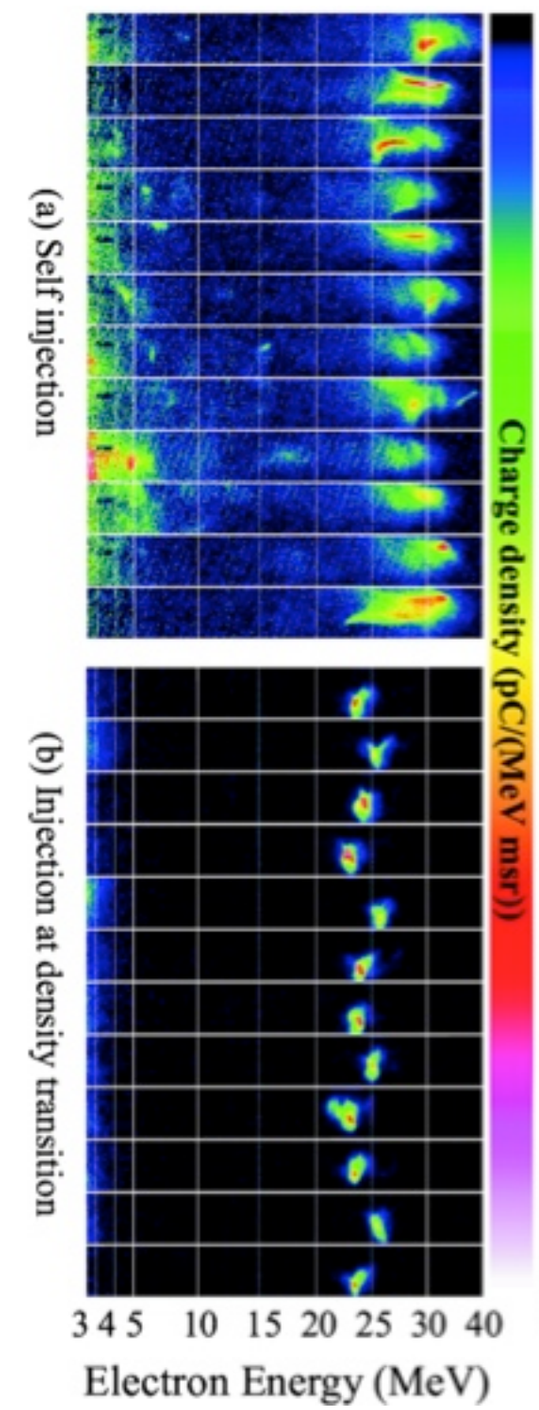
$$\lambda_p \propto n_e^{-1/2}$$



H. Suk et al., Phys. Rev. Lett. 86, 1011 (2001); H.Suk et al., Josa B (2004)

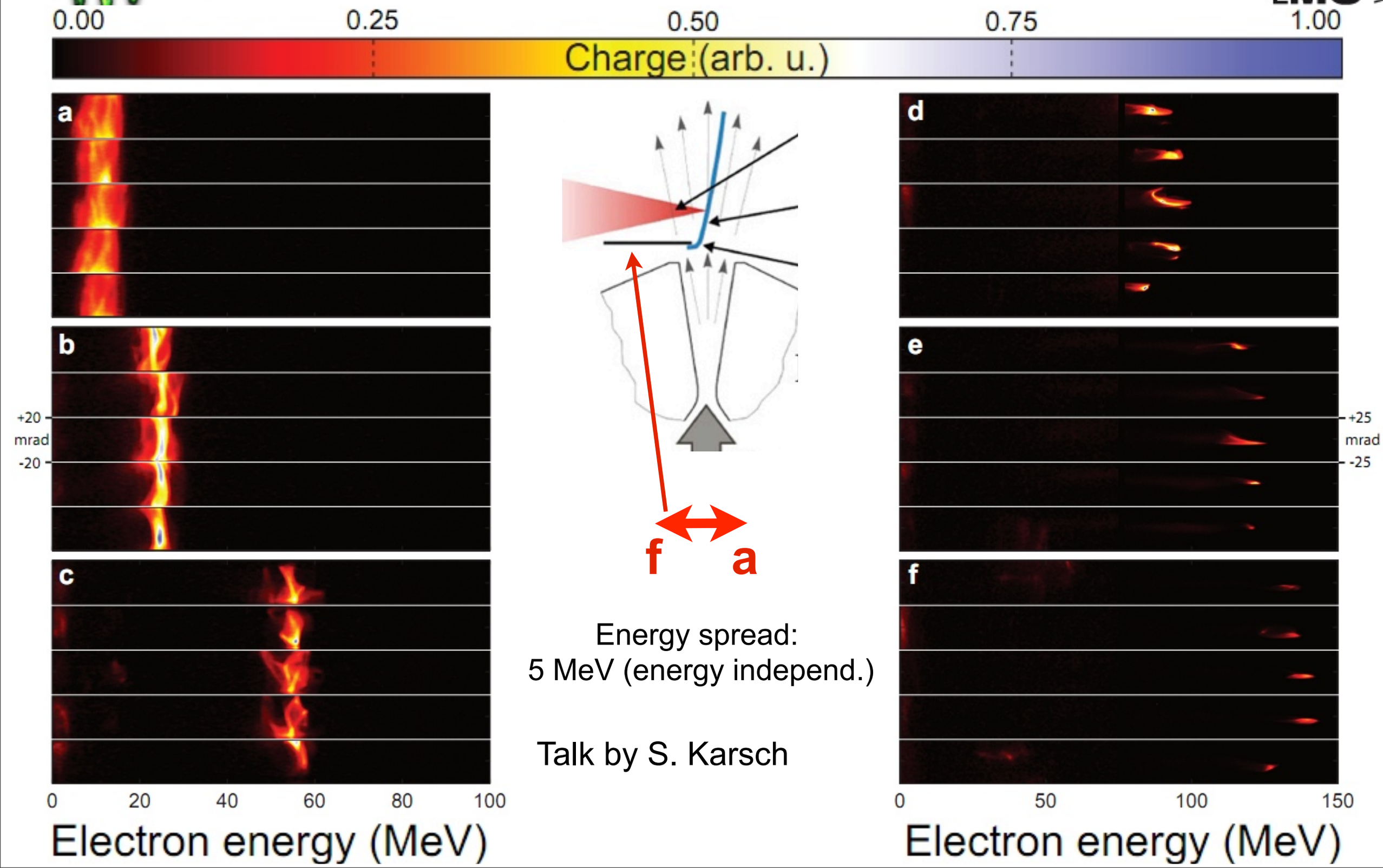
Shock-front produced with razor blade above supersonic gas jet





K. Schmid *et al.*, PRST-AB **13**, (2010)

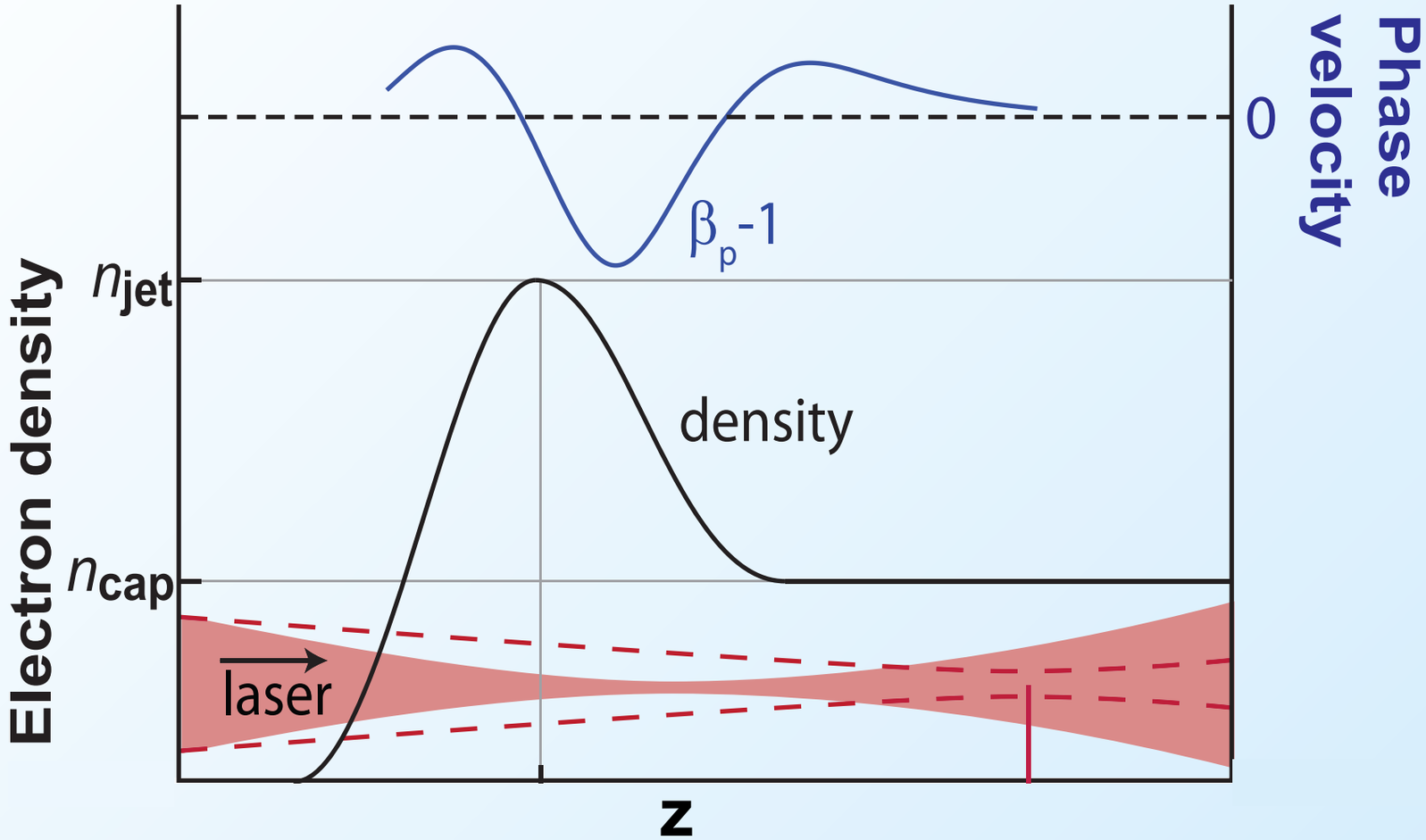
Razor Blade Location Tunes Electron Energy



Energy spread:
5 MeV (energy independ.)

Talk by S. Karsch

Phase Velocity And Wake Amplitude Control Via Laser Focusing In Tunable Plasma Lens



$$da_0/dz > 0$$

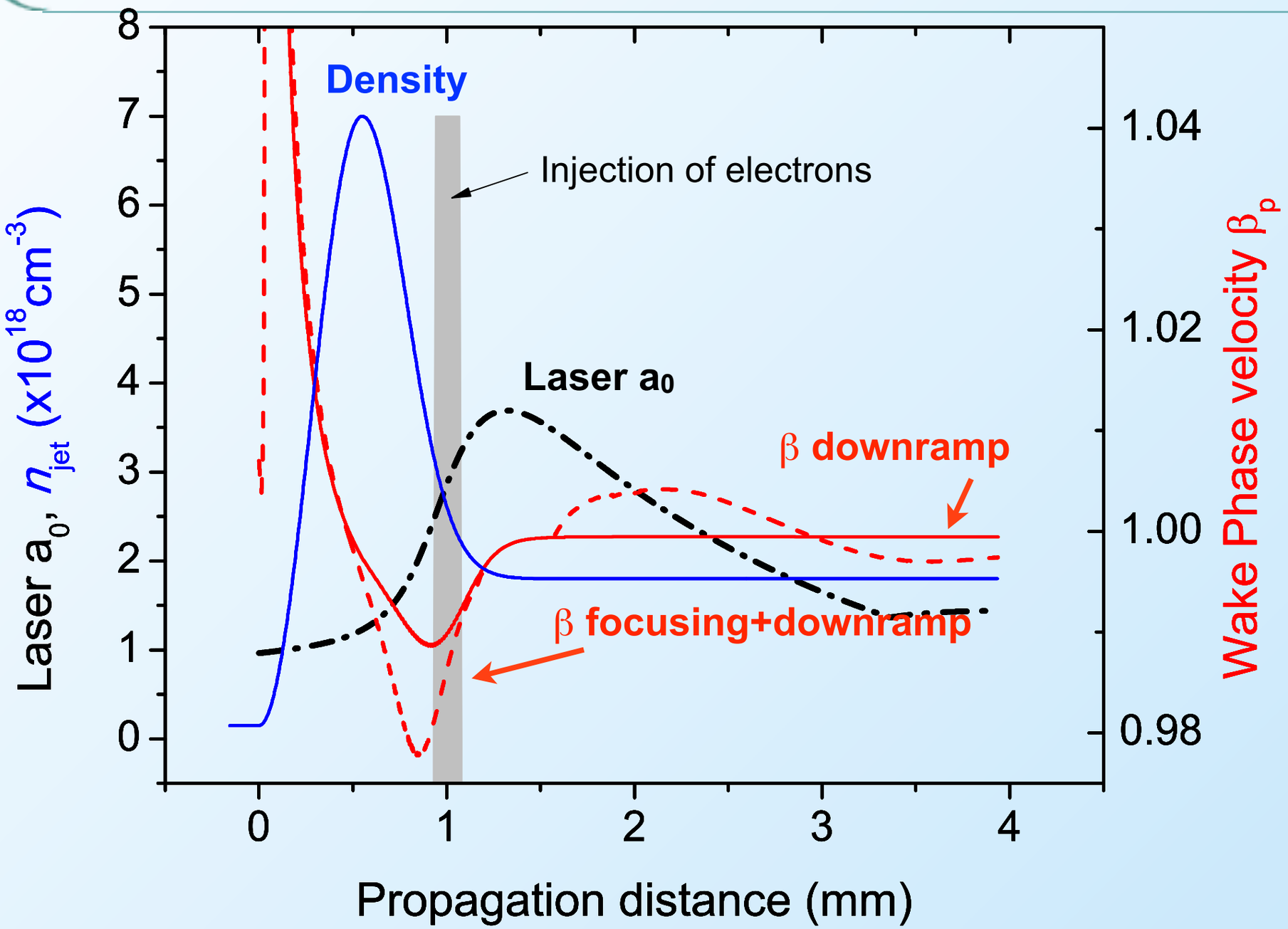
$$\Downarrow$$

$$d\lambda_p/dz > 0$$

- Increasing laser intensity lowers phase velocity through increase in non-linear plasma wavelength (enables trapping)
- Decreasing laser intensity (after focus) can terminate trapping
- Density can control effect via self-focusing (plasma lens)

Exp:Gonsalves et al., Nature Physics 7, 862–866 (2011)
Th:Schroeder et al., Phys. Rev. Lett. 106, 135002 (2011)

Simulation Shows Injection Enabled And Terminated By Controlling Wake Phase Velocity

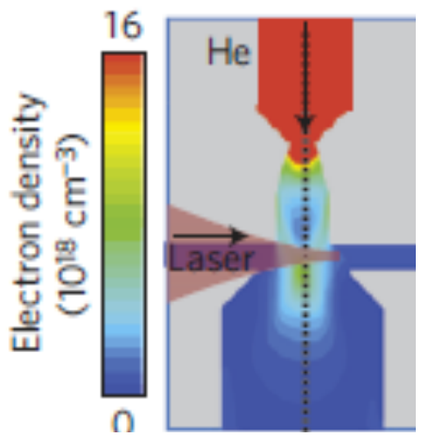


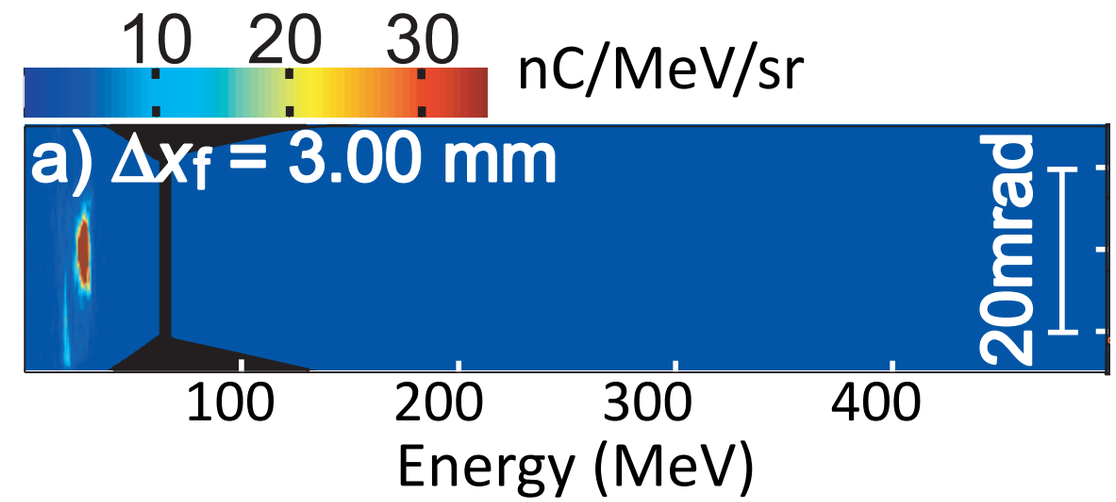
- Laser self-focuses due to $P>P_{crit}$ in high density gas jet
- Both downramp and increase in a_0 lower phase velocity
- Injection enabled when phase velocity low and a_0 high

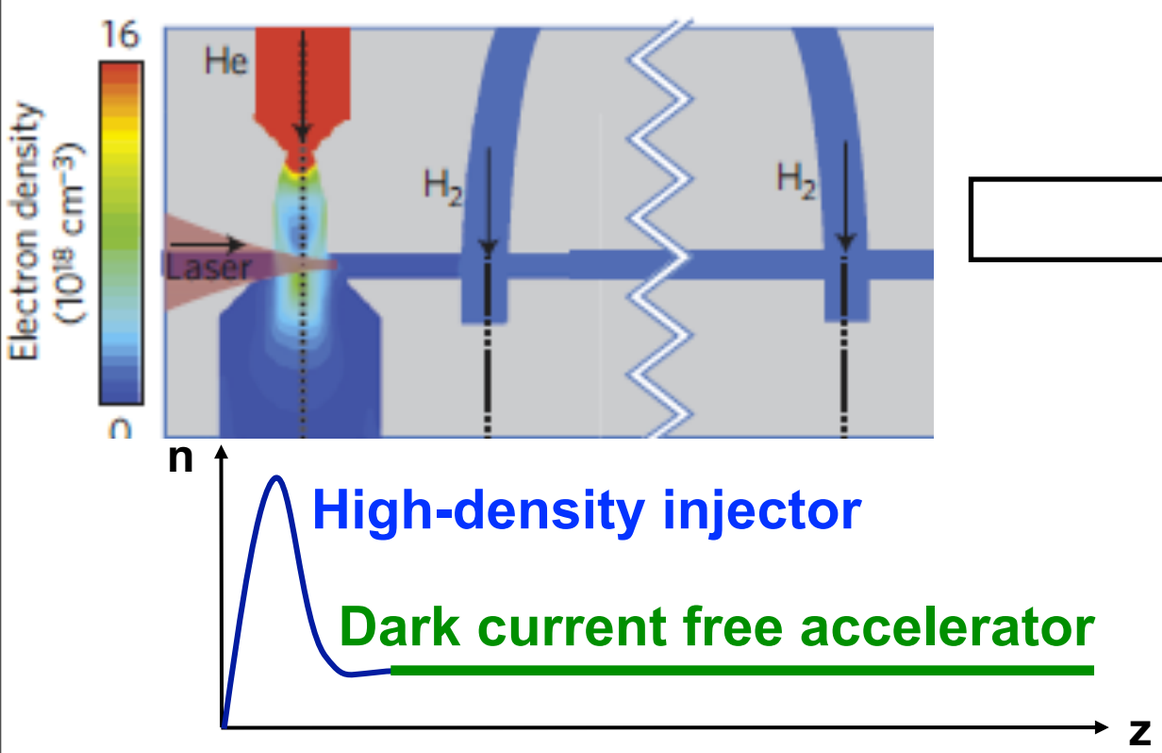
*Gonsalves et al., Nature Physics **7**, 862–866 (2011)*

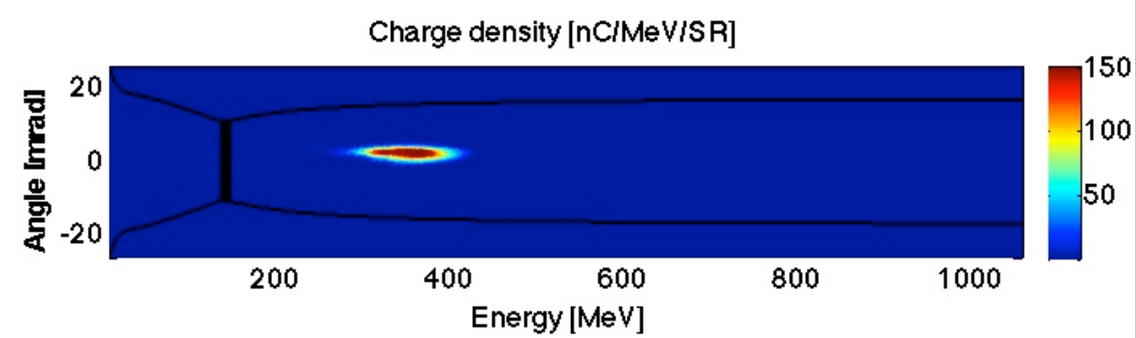
Benedetti et al., Proc. of AAC10 (2010)

Low Energy Beams Injected By Jet Accelerated In Low Density Capillary



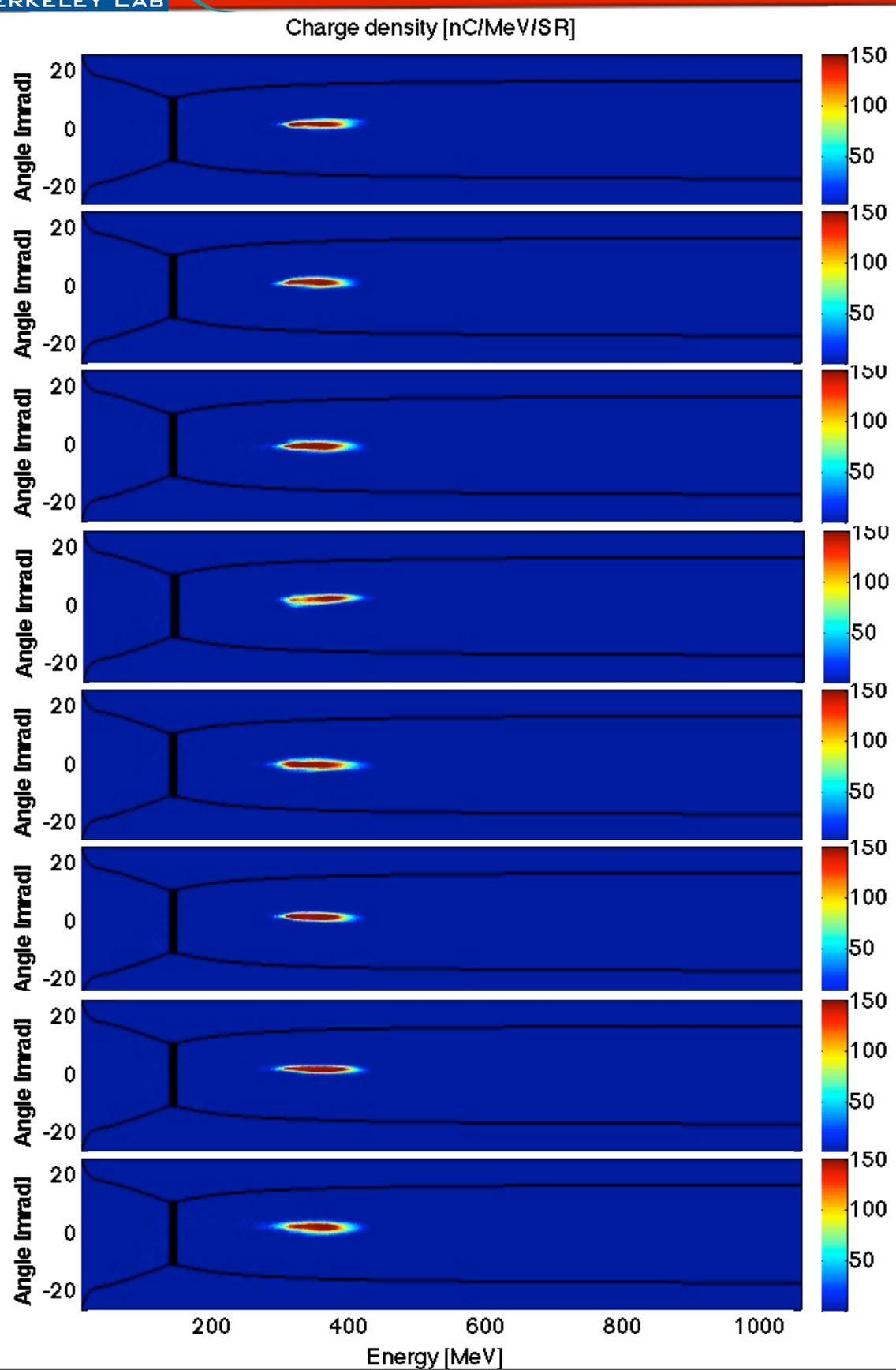


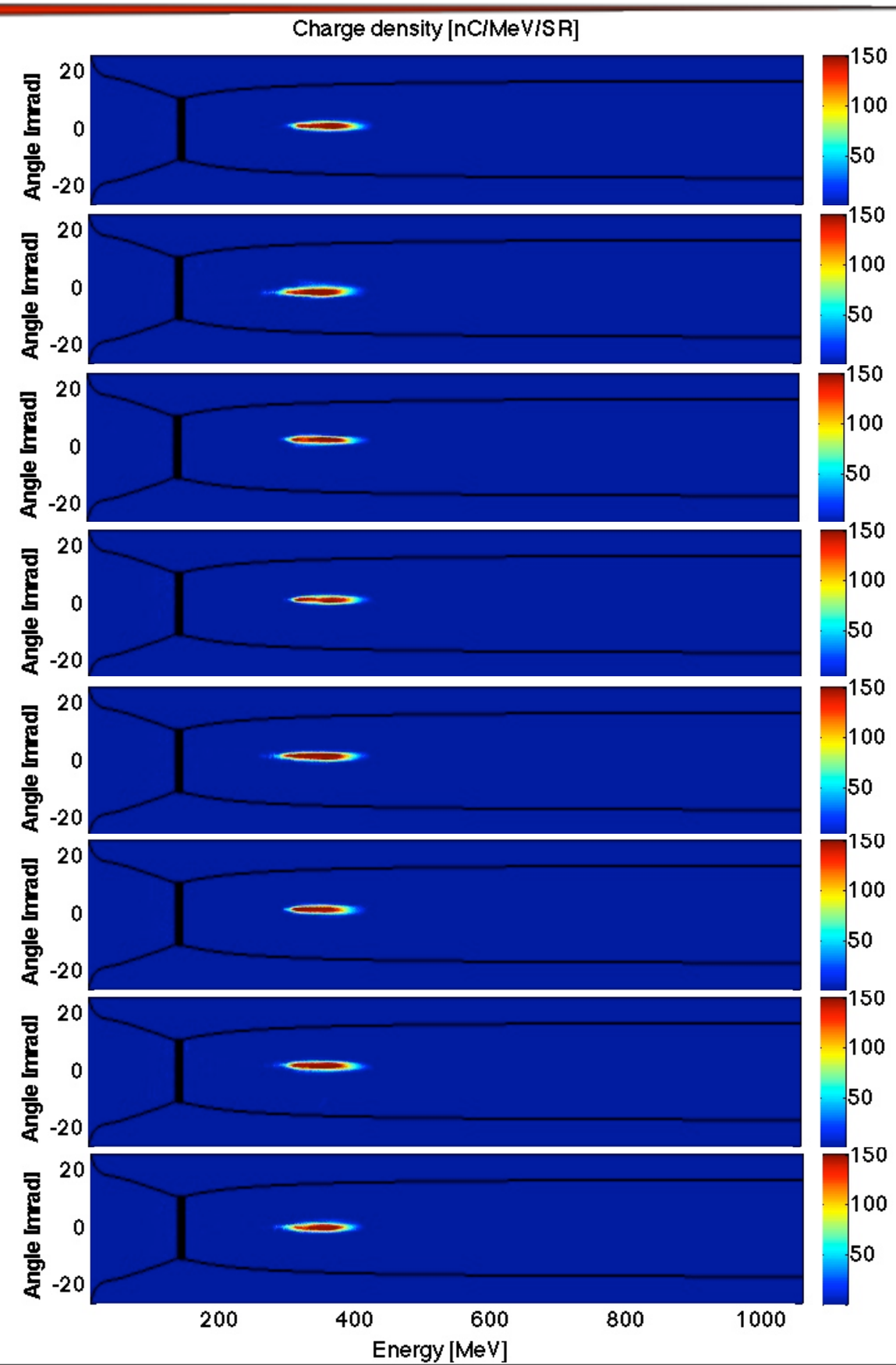




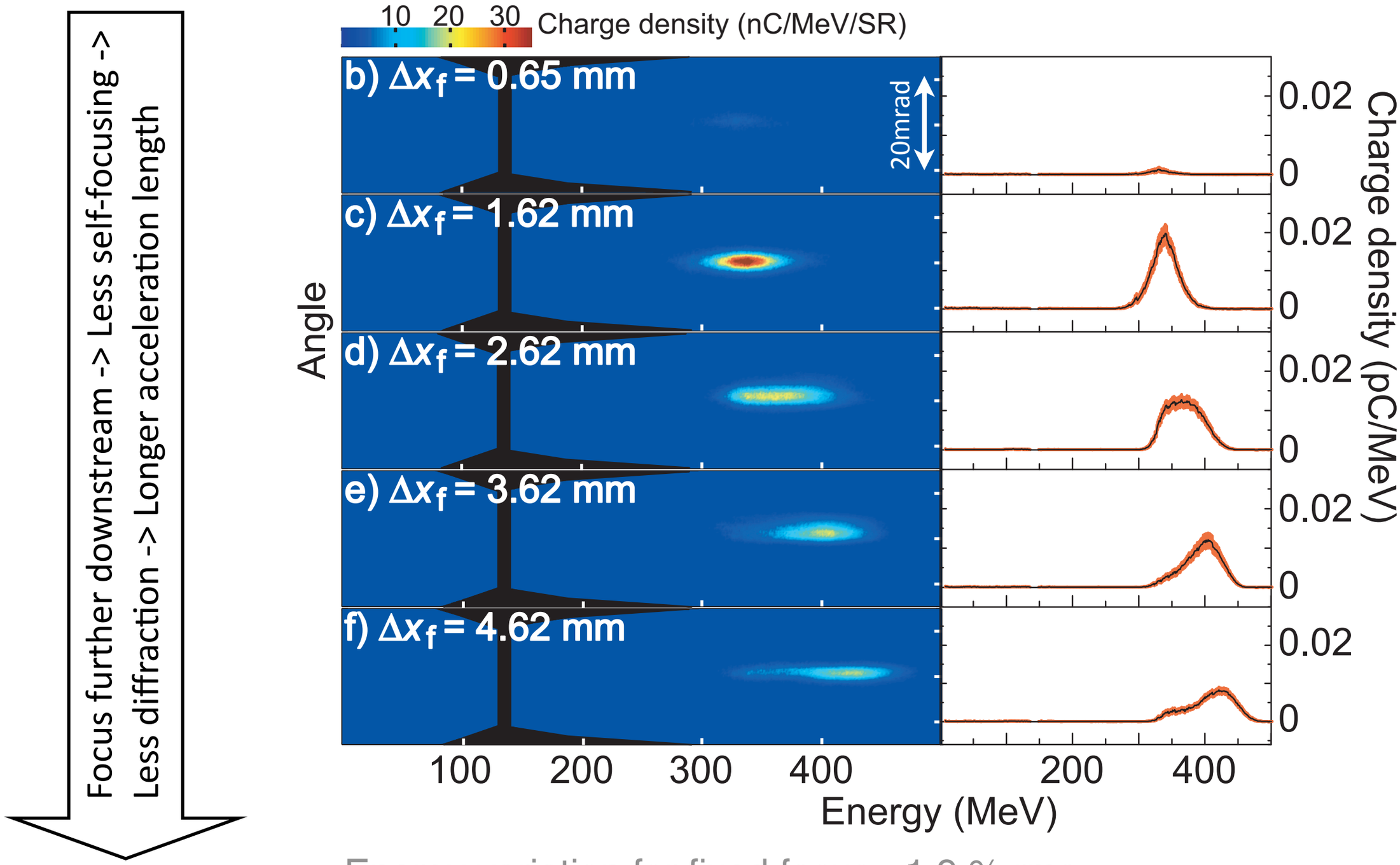
*Gonsalves et al., Nature Physics **7**, 862–866 (2011)*

Stable Electron Beams Produced With Jet+capillary Module; 2% Energy Variation: 6% Charge Variation





Tunable And Stable Electron Beams Produced With Jet+capillary Module

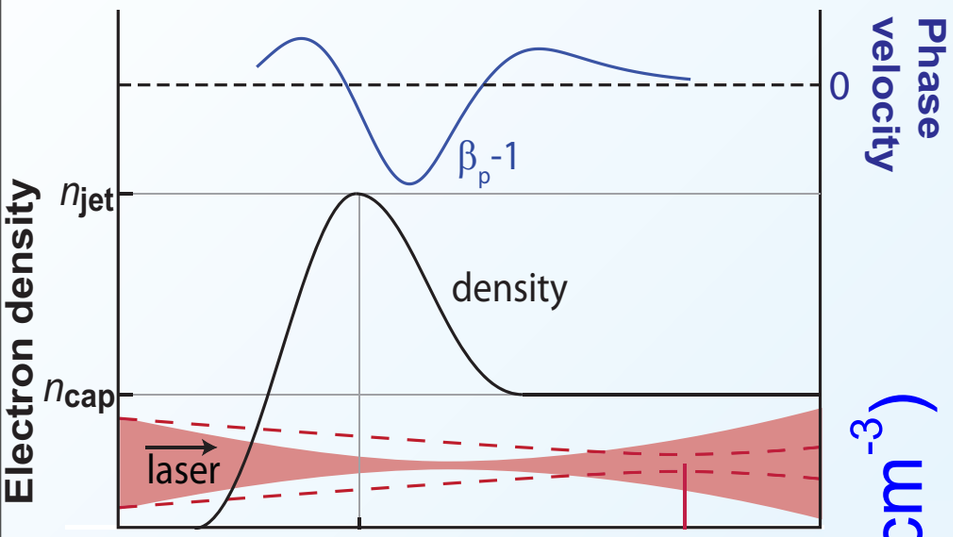


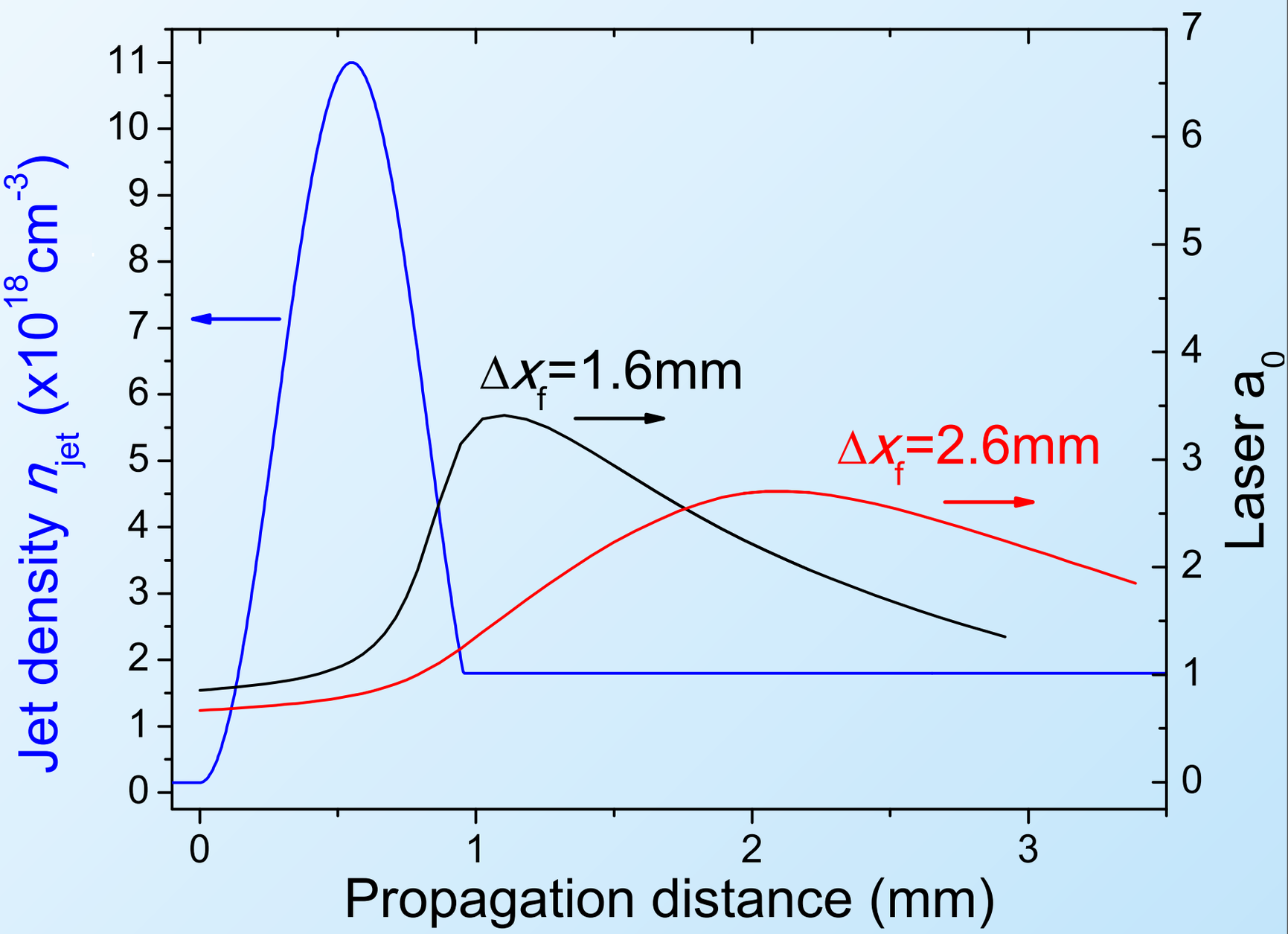
Energy variation for fixed focus <1.9 % rms
Divergence variation < 0.57 mrad rms

*Gonsalves et al., Nature Physics **7**, 862–866 (2011)*

BERKELEY LAB

Simulations Show Jet Is Tunable Plasma Lens

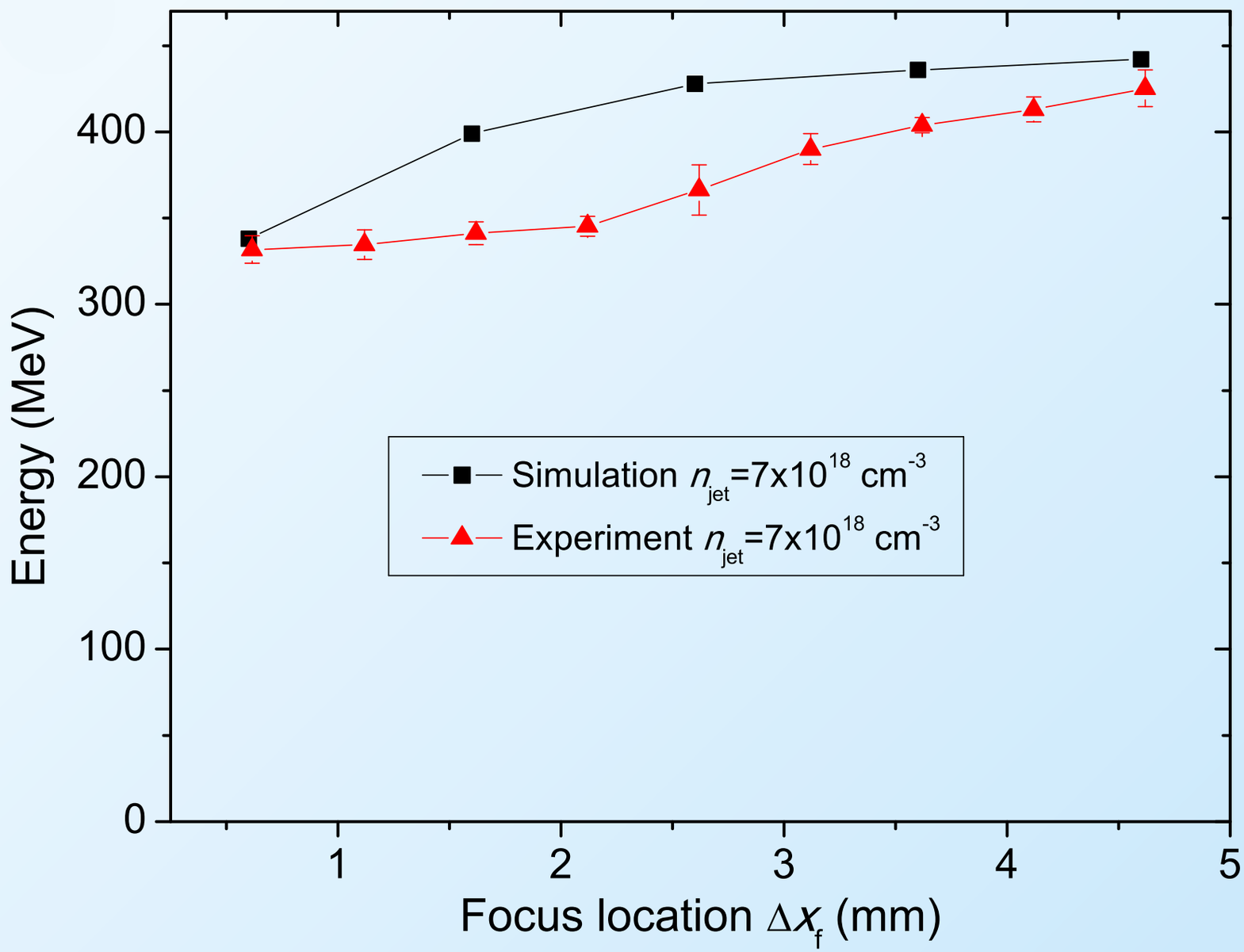




*Gonsalves et al., Nature Physics **7**, 862–866 (2011); Talk by S. Y. Kalmykov WG1*

Simulations Reproduce Energy Trend And Show Role Of Diffraction In Energy Gain

$$\Delta\gamma \simeq \pi^2 \left[(a_0^2/2)/\sqrt{1 + a_0^2/2} \right] (Z_{\mathrm{eff}}/\lambda_{\mathrm{p0}})$$



*Gonsalves et al., Nature Physics **7**, 862–866 (2011)*

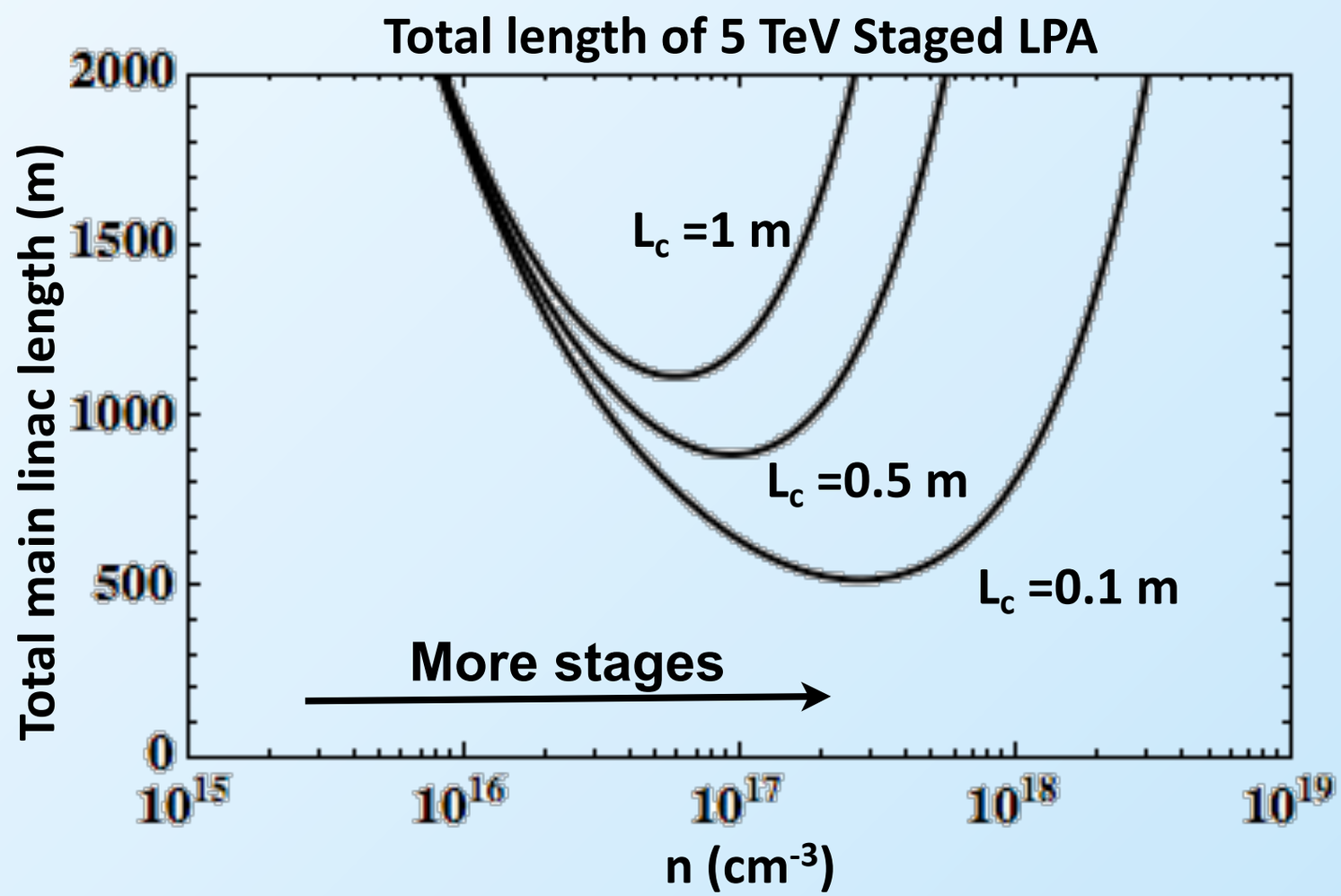
Percent-level Energy Spread Also Observed From Jet +capillary

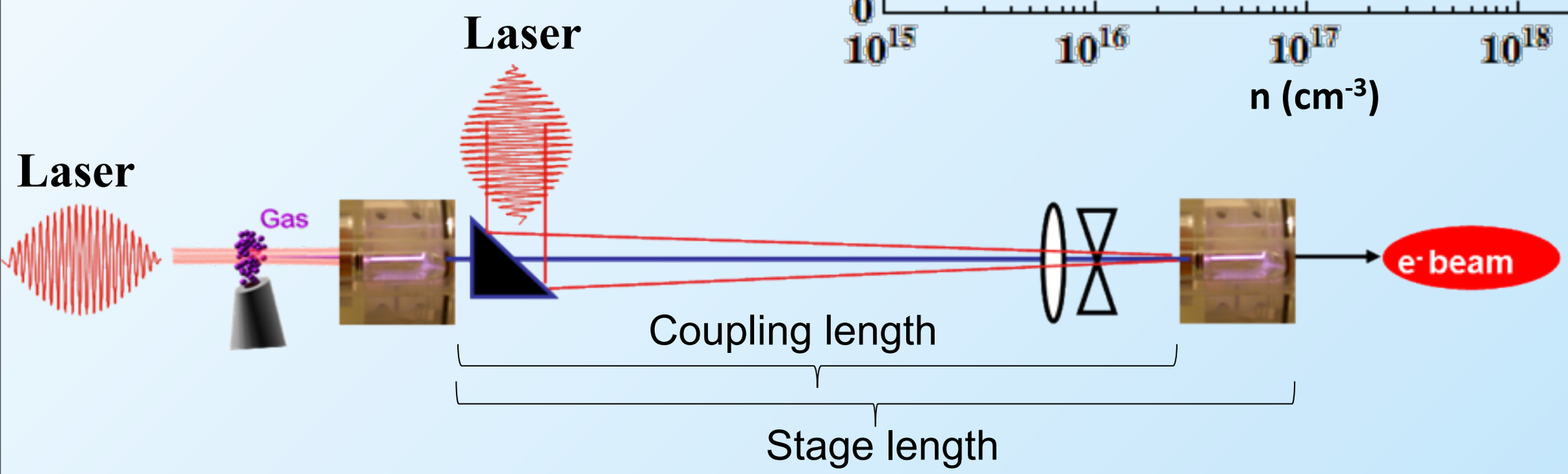
Material not released

Staging

Staging Laser Accelerators To Overcome Laser Depletion. Choice Of Density And Laser Coupler Determines Accelerator Length

- Increase beam energy
- Witness beam experiments with arbitrary delay (electron beam intrinsically synchronized with laser driver)





C.B. Schroeder et al., PRST-AB **13** (2010) Panasenko et al., AAC08

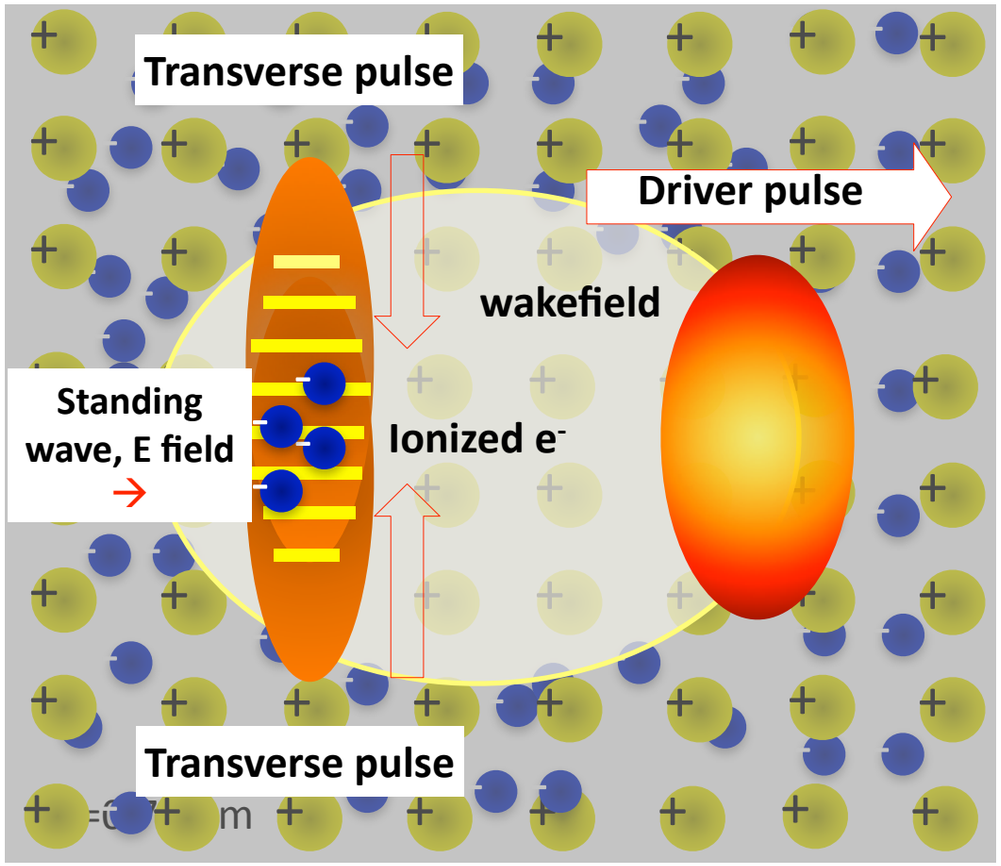
Tape Drive Plasma Mirror Demonstrated At Joule Level And Reflected Beam Powered 2nd Stage

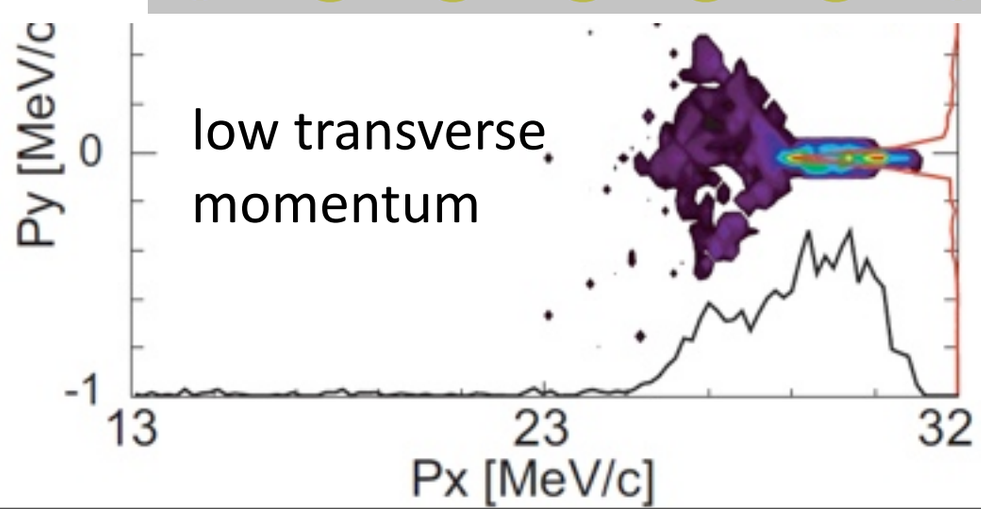
Material not released

see talk T. Sokollik
this afternoon WG1

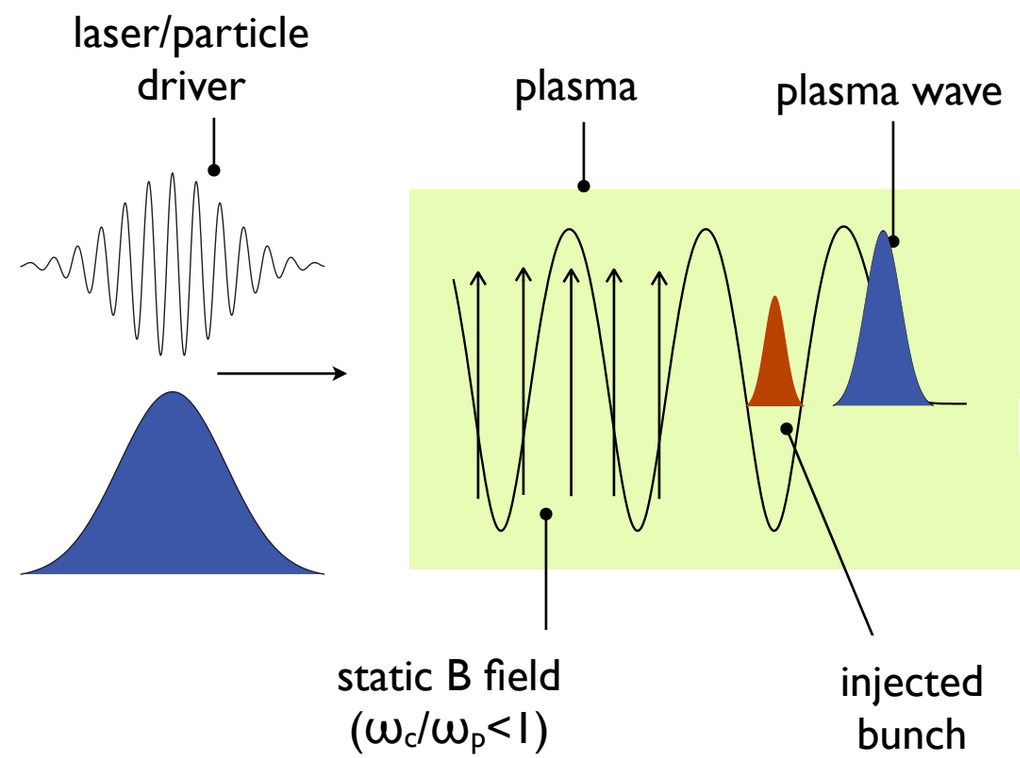
Community Consistently Inventive - The Future Is Bright!

- Transverse colliding pulses with ionization
  M. Chen et al., Phys. Plasmas **19** (2012)
  M. Chen et al., Workgroup 1, AAC 2012
  M. Chen talk in WG1 Wednesday afternoon

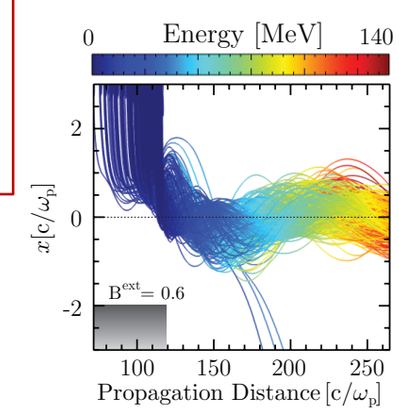




- Injection with static magnetic field
  - J. Vieira, et al., Phys. Rev. Lett **106** 225001 (2011)
  - J. Vieira talk in WG1 Thursday afternoon

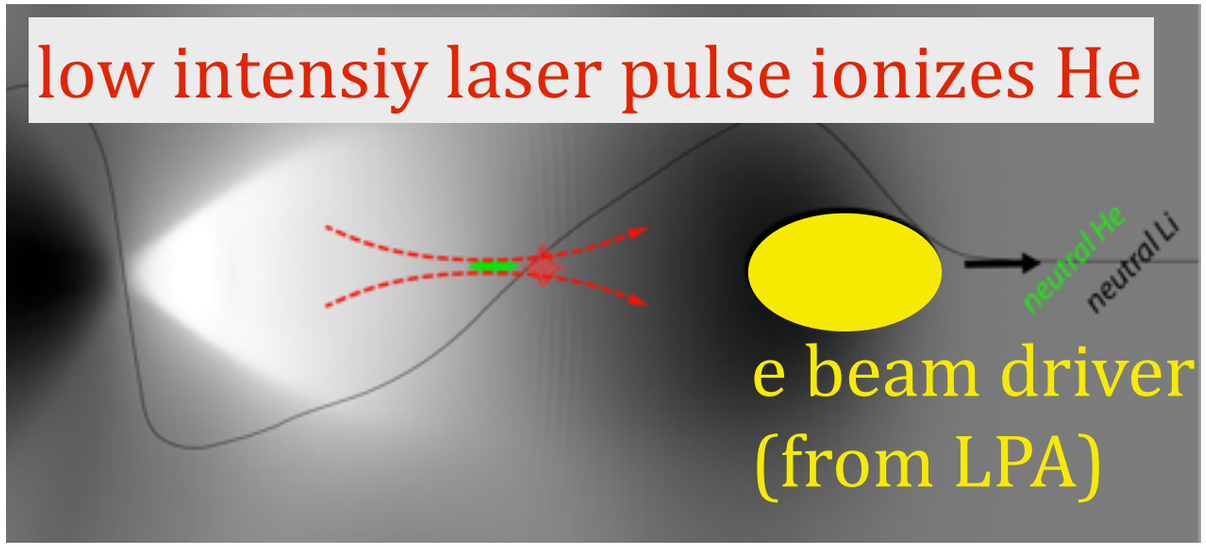


synchronized betatron oscillations



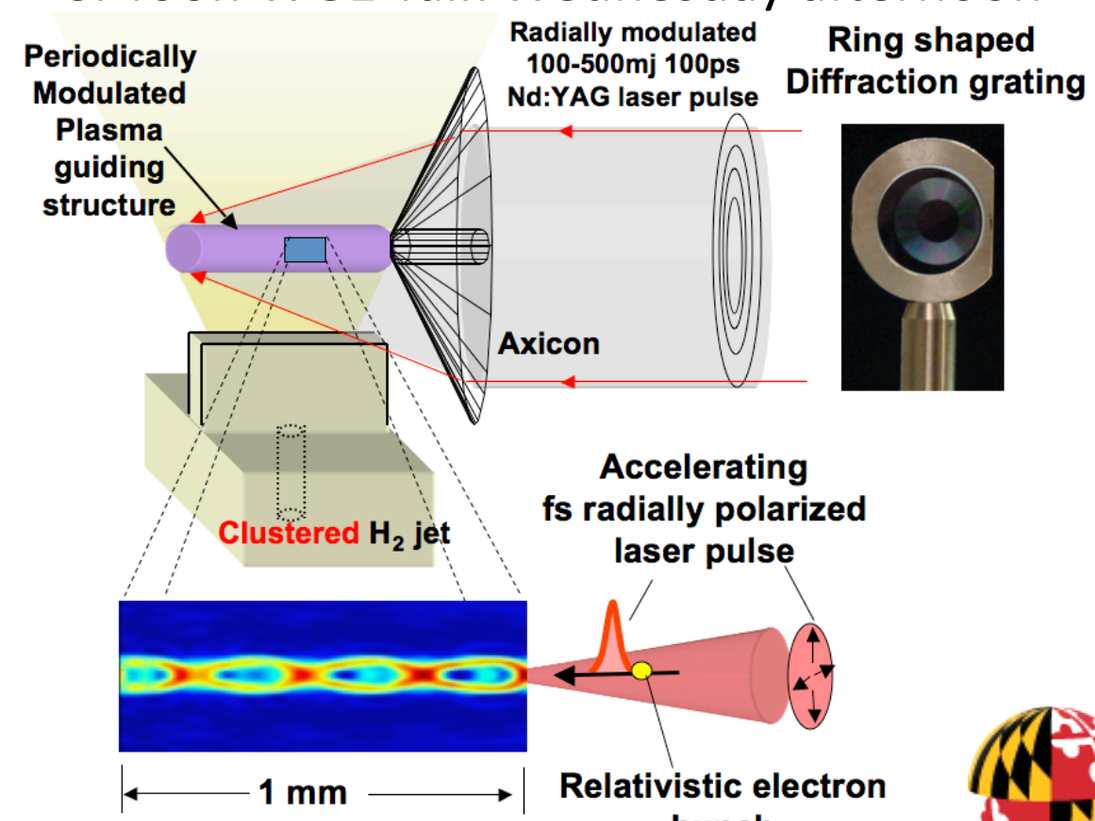
Community Consistently Inventive - The Future Is Bright!

- Trojan horse scheme UCLA
  - B. Hidding et al., PRL **108**, 035001, 2012
  - see Hidding talk in WG4 Tuesday afternoon
  - E 210: 2013 @FACET



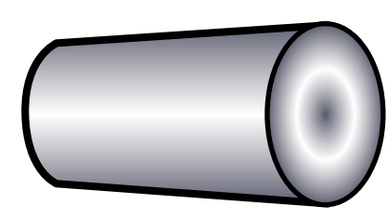
low intensity, cold electrons, low emittance

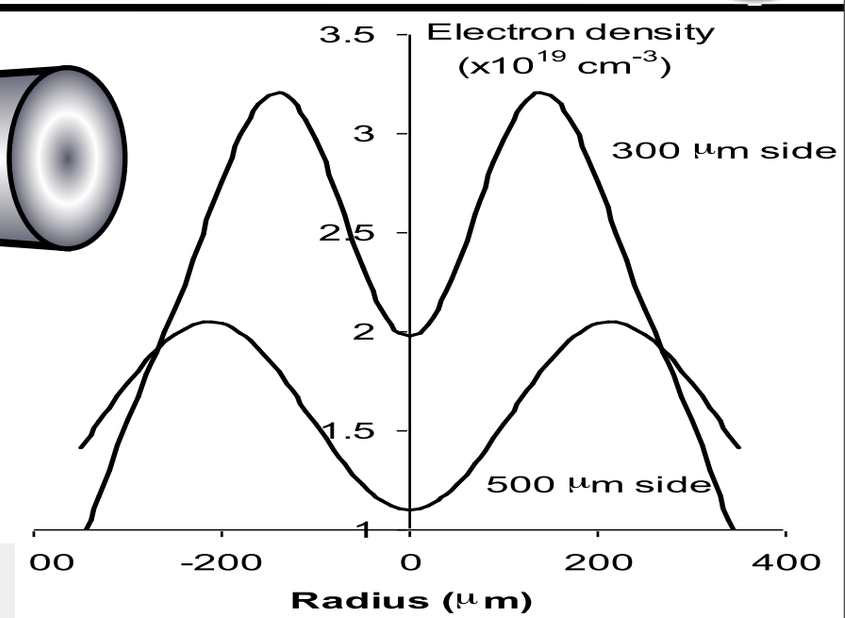
- DLA with radially polarized pulses
  - S. Yoon et. al., submitted to PRST-AB (2012)
  - S. Yoon WG1 Talk Wednesday afternoon



B. Layer *et. al.*, PRL, **99**, 035001 (2007)

- Tapered capillary for optimized stage
  - D. Kaganovich et al., Appl. Phys. Lett. **75**, 772 (1999)
  - D. Kaganovich et al., Appl.Phys.Lett. **72**, 759 (2001)
  - Talk H. Suk WG1 Wednesday morning
  - Talk W. Rittershofer WG1 Wednesday morning





UNIVERSITY OF OXFORD

High Intensity Laser Lab

Summary And Challenges For The Future

- Beam quality, stability, tunability all improving
  - Self-injection experiments continue to improve
  - Sophisticated injection techniques have demonstrated precise injection control
  - Advantages of new PW laser systems starting to be shown and more on the way (BELLA 1Hz PW)
- Key Challenges
  - 0.1% energy spread to realize applications
  - Independent control over beam parameters (energy spread, charge)
  - Simulations predicting experiments